Pavement Marking Performance Analysis

by

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16. Abstract

This research evaluated pavement marking performance and developed useful degradation models for thermoplastic and paint pavement markings which can help North Carolina meet the pending FHWA minimum retroreflectivity requirements. The impacts of several important factors (such as lateral location, directionality, region, and pavement roughness) on pavement marking retroreflectivity were evaluated. With two large datasets in hand, we determined whether these factors had significant impacts on marking retroreflectivity. Image processing techniques were used to analyze pavement marking surface glass bead density. We were able to explain why paint marking retroreflectivity values degraded over time by evaluating the impact of bead density on paint marking retroreflectivity. The research reviewed existing marking retroreflectivity degradation models and developed useful new models for both thermoplastic and paint pavement markings in NC. The research presented a transportation asset management system framework for estimating the current and future condition of pavement markings. The research outcomes enable the NCDOT have a better understanding of thermoplastic and paint pavement marking performance, which can lead to cost saving by maximizing pavement marking service lifecycles.

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EXECUTIVE SUMMARY

Pavement markings, like traffic signs, are considered to be traffic control devices having the function of controlling traffic and encouraging safe and efficient vehicle operation according to the American Association of State Highway and Transportation Officials (AASHTO). Pavement markings generally have a shorter service life than the pavement on which the markings are applied. Markings need to be restriped when their retroreflectivity values fall below a minimum level or when a portion of the markings are worn away by the traffic. Understanding pavement marking performance is important to maximize the material's service lifecycle which can eventually reduce the costs of markings. This research evaluates pavement marking performance characteristics on NC highways and presents a pavement marking asset management system scheme that will enable the NCDOT to effectively implement pending new Federal standards on pavement markings.

The research found that there was a significant difference in the rate of retroreflectivity degradation between edge lines and centerlines for both yellow and white thermoplastic markings. The results indicated that edge lines degraded at a slower rate than center or skip lines for both white and yellow thermoplastics. Both un-weighted and weighted ANOVA analyses indicated that there was a consistent 85 percent or greater probability that edge lines and center lines degraded at different rates from six months through five years for both yellow and white thermoplastic markings.

Paint pavement marking centerline retroreflectivity values measured in the direction of paint striping were found to be significantly higher than the values measured in the opposite direction. The differences were normally in the range of 20-50 mcd/m^2/lux but the difference could be as large as 95 mcd/m^2/lux based on the field collected data. The results indicated that the lower average retroreflectivity value for a yellow centerline, measured in the opposite direction from the direction of paint striping, should be used to compare with the future FHWA minimum standard to determine whether or not the centerline meets the standard.

We developed a computer-aided counting method to analyze glass bead images to obtain glass bead density values. Then, we conducted a correlation study between pavement marking retroreflectivity and bead density. The study found that the normal range of bead density we observed was 9-24 percent of the paint marking surface. Glass bead density had a significant impact on marking retroreflectivity. Higher glass bead density led to higher marking retroreflectivity. Furthermore, white edge markings had conclusively higher retroreflectivity values than yellow center markings when the bead density values were the same.

The researchers used ANOVA and longitudinal data analysis methods to investigate the impact of region on pavement marking retroreflectivity. The results showed that in the mountain area the thermoplastic pavement marking retroreflectivity values degraded faster than in the central and coastal area. But, the differences were not statistically significant because the variations within each region were relatively large.

Linear regression models were developed for thermoplastics on asphalt. The independent variables of the recommended model included time, initial retroreflectivity measurement, AADT, color, and lateral location, which were all validated by statistical effects tests. The research found that for an AADT of 10,000 vehicles per day, the expected service life for thermoplastics on asphalt ranged from 5.4 years to 8.75 years depending on the color and lateral location. The result also showed that AADT had a small but significant impact on the degradation of thermoplastic pavement markings.

We established linear mixed effects models (LMEM) for white edge and yellow center pavement markings. The LMEM results showed that the fixed intercept and fixed slope were 310 mcd/m^2/lux and -75 mcd/m^2/lux per year for white edge new markings, and were 143 mcd/m^2/lux and -25 mcd/m^2/lux per year for yellow center new markings. The random intercepts and slopes varied in a wide range among different pavement markings, which means that marking performances changed significantly from one road to another. The estimated average lifecycles for white and yellow paint markings were 2.7 and 3.1 years, respectively.

The research developed a transportation asset management system framework for estimating the current and future condition of pavement markings. We described the data structure, in the form of a physical model, integrating a pavement marking relational data schema with existing information technology systems. The system included an algorithm which implements the data structure and predictive models to estimate the condition of the asset at any point in time or space on the highway system. Using either measured data or predicted data the system gives managers an opportunity to decide on the best possible condition state of the asset and perform queries or optimizations. Thus, pavement marking managers can develop cost effective strategies for pavement marking asset management.

The research outcomes help the NCDOT better understand thermoplastic and paint pavement marking performance, which can lead to cost saving by maximizing the marking service lifecycle. The NCDOT can better allocate its limited equipment and personnel resources by using performance-based pavement marking management. The results of this research provide a consistent measurement method and an analysis procedure for marking retroreflectivity data, which can help transportation agencies meet future FHWA minimum retroreflectivity standards and reduce their liabilities.

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1.0 INTRODUCTION

Pavement markings, like traffic signs, are considered to be traffic control devices having the function of controlling traffic and encouraging safe and efficient vehicle operation according to the American Association of State Highway and Transportation Officials (AASHTO). For highways and streets three general types of markings are in use: pavement markings, object markers, and delineators [AASHTO 2004]. Pavement markings include centerline stripes, lane lines, and edge lines. These may be supplemented by other pavement markings such as approaches to obstructions, stop and crosswalk lines, and various word and symbol markings [AASHTO 2004]. The Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways specifies that pavement markings are commonly placed using paint and thermoplastic materials although other suitable marking materials can also be used [FHWAa 2003].

Pavement markings generally have a shorter service life than the pavement on which the markings are applied. Markings need to be restriped when their retroreflectivity values fall below a minimum level or when a portion of the markings are worn away by the traffic. The first-time installation and later restriping of pavement markings bring a high maintenance cost to the transportation agencies. For example, the North Carolina Department of Transportation (NCDOT) is charged with managing all aspects of a 78,000-mile roadways system. Pavement markings cost NC approximately $14.5 million a year in contractor-performed work which represents two percent of the $700 million NCDOT highway maintenance budget [Sitzabee 2008]. Understanding pavement marking performances is important to maximize the material's service lifecycle which can eventually reduce the costs of markings.

At the present time, no national standard specifies the minimum retroreflectivity levels below which the markings should be replaced. However, a Congressional mandate, section 406 of the 1993 Department of Transportation and Related Agencies Appropriations Act, directed the Secretary of Transportation to revise the MUTCD to include a standard for minimum levels of retroreflectivity that must be maintained for traffic signs and pavement markings [Vereen et. al. 2004]. The minimum retroreflectivity levels and maintenance methods for traffic signs were published in revision 2 of the 2003 version of the MUTCD. The final rule has been effective since January, 2008 [FHWA 2008]. The Federal Highway Administration (FHWA) is working with other research agencies to establish a similar minimum retroreflectivity standard for pavement markings.

1.1 Research Objectives

The NCDOT has collected several years of pavement marking retroreflectivity data through a private contractor, Precision Scan LLC. The intent of the data collection was to use the data as a quality control tool for managing a large amount of contractor applied pavement markings. With a large database now in hand, the NCDOT asked whether the data can be used to better understand the pavement marking performances.

The minimum retroreflectivity requirement for pavement markings is expected to be included in MUTCD soon. When the minimum standard is published, it will be a mandate for NCDOT and other highway agencies to meet the minimum requirements established by FHWA.

The overall objectives of this research are to provide the NCDOT with a better understanding of pavement marking material performance; to maximize the material's lifecycle and minimize replacing markings which still have sufficient retroreflectivity; and to help NCDOT meet the pending FHWA minimum requirements and reduce the liability of possible lawsuits.

This research focuses on four major problems. First, the impacts of several important factors (such as lateral location, directionality, region, and pavement roughness) on marking retroreflectivity are unclear. With two large datasets, we can determine if these factors have significant impacts on marking retroreflectivity. Second, we provide insights into the reasons why pavement markings lose retroreflectivity over time by determining the impact of bead density on paint marking retroreflectivity. Third, we evaluate existing degradation modeling techniques and establish useful retroreflectivity degradation models for both thermoplastic and paint pavement markings. Fourth, the study presents an integrated transportation asset management system framework for estimating the current and future condition of pavement markings

1.2 Research Scope

The scope of this research is the thermoplastic and paint longitudinal pavement markings on all roads open to public travel. The majority of marking materials in use are thermoplastics and paints. They are estimated to make up 89% of all marking materials in the US according to a survey by Migletz and Graham [2002]. In North Carolina, the NCDOT primarily uses four types of materials which are paint, thermoplastics, epoxy, and polyurea. More than 90% of its total marking mileages are thermoplastics and paint [NCDOT 2008]. The epoxy and polyurea are mainly applied on concrete pavement surfaces in the mountain region of the state.

Two main sources of retroreflectivity data have been pursued in this research. The first source of data was from the NCDOT Work Zone Traffic Control Unit (WZTCU). The NCDOT has been collecting pavement marking retroreflectivity data via mobile devices (Laserlux) by a contractor, Precision Scan LLC. Nearly 30,000 lane miles of marking data were collected thought NC from May 2001 to July 2007. The collected data were mostly on thermoplastic markings. The paint markings were contractor-applied and the sample size of those was small in NCDOT database. The second source of retroreflectivity data were measurements of paint markings by the NCSU research team. The research team collected paint marking retroreflectivity data on secondary roads in NC because they comprise the majority of roadways. Using a handheld retroreflectometer LTL 2000, we collected four rounds of paint data from November 2007 to May 2009.

Most studies of this research were therefore based on those two sources of data. Thermoplastic studies generally used the NCDOT data, while paint studies used NCSU data. Other sources of data, such as pavement roughness data collected by NCDOT pavement management unit, were also utilized in the analysis and were noted when they were used.

The extent of the data collection activity of this research was tremendous compared to similar research reported in the literature. The relatively large datasets enabled us to evaluate the impacts of several factors on pavement marking retroreflectivity and to create valid retroreflectivity degradation models.

Though the NCDOT follows a typical pavement marking management procedure, readers should note that the direct results of this research (such as the retroreflectivity degradation models) may not be directly applicable to other geographic regions in the US and other countries. The readers in other geographic regions could use the methodologies and procedures presented here. However, they need to use their own data and draw conclusions based on the data collected in their regions. Though this research concentrates on the paint and thermoplastic material, the methodologies are also applicable to other types of marking materials (e.g. epoxy and polyurea).

1.3 Outcomes and Benefits

The results of this research are that the lateral location of pavement markings has a significant effect on marking retroreflectivity readings. The impact of directionality on paint pavement marking retroreflectivity is also found to be significant. Glass bead density is found to have a significant impact on marking retroreflectivity. Higher glass bead density leads to higher marking retroreflectivity. There is an impact of region (coast, central, and mountain) on thermoplastic pavement marking retroreflectivity but it is not statistically significant. Other important outcomes of this research are valid retroreflectivity degradation models for both thermoplastics and paints and a proposed integrated transportation asset management system framework for estimating the current and future condition of pavement markings.

The research outcomes will help the NCDOT better understand thermoplastic and paint pavement marking performance, which can lead to cost saving by maximizing the marking service lifecycle. The NCDOT can better allocate its limited equipment and personnel resources by using performance-based pavement marking management. The results of this research will provide a consistent measurement method and analysis procedure for marking retroreflectivity data, which can help transportation agencies to meet future FHWA minimum retroreflectivity standards and reduce their liabilities.

This research is also beneficial to future researchers. The collected retroreflectivity datasets can be used by others. The modeling method and procedure can be used to create models for other types of marking material or for other similar transportation assets.

1.4 Report Organization

The remainder of the report is organized into chapters that present each of the major analyses performed during this project. Chapter 2 introduces the lateral location study. Chapters 3 and 4 present the paint marking directionality and bead density studies. Chapters 5 and 6 evaluate the impacts of region and pavement roughness on marking retroreflectivity measurements. Chapters 7 and 8 present the degradation models for thermoplastic and paint markings. Chapter 9 discusses a framework for a pavement marking management system. Chapters 10-12 present conclusions, recommendations, and technology transfer plans of the research project. Chapters 13 and 14 are references and appendices for the report.

2.0 STATISTICAL VALIDATION OF THE EFFECT OF LATERAL LINE LOCATION ON PAVEMENT MARKING RETROREFLETIVITY DEGRADATION

This chapter focuses on the impact of lateral line location on pavement marking degradation over time. Previous studies have validated that color, material type, and surface type all impact pavement marking degradation. Current literature indicates that color, pavement surface, and material type, are all valid independent variables, which do affect the rate of change in pavement marking performance. However, the affect of lateral line location remains a question.

It is a common assumption that the lateral location has an effect on the rate of retroreflectivity degradation, and that the center line or center skip lines will degrade faster than edge lines due to traffic. However there is no evidentiary validation of this statement available in current literature. Specifically, this research used statistical analysis to determine whether lateral line location was a significant factor to be considered in degradation of pavement marking retroreflectivity.

This study will quantify the statistical significance of lateral line location on pavement marking degradation and presents the management implications. As will be discussed, the data used for the analysis was from a study conducted over a five-year period in NC and the analysis focused solely on yellow and white thermoplastic markings on an asphalt base course.

This study is one component of a larger study to determine long-term performance characteristics of pavement markings in NC and provide an asset management strategy. NCDOT has determined that it needs to develop an optimized pavement marking strategy that is performance based in order to maximize cost savings and prepare to comply with the impending Federal Highway standards. Data driven analysis, as advocated by Wilson-Orndoff, lays the foundation for using quantifiable measures to formulate pavement marking asset management strategies [Wilson-Orndoff 2003]. The objective at the NCDOT is to formulate a pavement marking performance model that can accurately predict the life cycle of pavement markings and then use this in an asset management framework to accurately determine when each segment of road needs to be remarked. As previously determined, improvements in pavement marking quality is directly correlated with reduced probability of an accidents [Al-Masaeid and Sinha 1994].

2.1 Background

Previous research by others focused on the impact of pavement marking retroreflectivity on a driver's visibility and how pavement markings degrade over time. Understanding retroreflectivity performance over time is important to establishing a pavement marking strategy that maximizes the material's lifecycle by minimizing replacement of pavement markings that still have sufficient retroreflectivity. There is a gap in the current knowledge of how the lateral line location affects the rate of degradation. This section provided a basic description of pavement marking materials and retroreflectivity measurement, and highlights two previous studies on pavement markings.

2.1.1 Pavement Marking Materials

According to the American Association of State Highway and Transportation Officials (AASHTO, 2004), pavement markings are defined as center stripes, lane lines, no-passing barriers, and edge striping. In all cases pavement markings refer to long-lines and should not be confused with object markings or delineators. The term lateral line location deals with the transverse location of the line along the pavement.

Pavement markings are first classified as durable and non-durable. Non-durable materials are expected to have a service life of one year or less, while durable materials should have a service life greater than one year. Non-durables are typically considered to be paint-based markers while most other materials fall under the durable classification. Table 2.1 lists the most common materials used in pavement markings across the US [Migletz and Graham 2002]. The most common pavement marking material is paint, which is typically replaced annually, based on need and transportation department budget cycles. The second most common material is a raised thermoplastic coating that is laid on top of the base material. Other common materials are polyesters and epoxy. The four materials currently in use by the NCDOT are paint, thermoplastics, epoxy, and polyurea. These are shaded in Table 2.1.

Table 2.1. Pavement Marking Materials

	Pavement Marking Material Type	**Percentage of Use**
1	Waterborne paint	59.9
2	Thermoplastics	22.7
3	Conventional solvent paint	6.5
4	Polyester	3.8
5	Epoxy	2.7
6	Preformed tape – flat	< 1.0
7	Preformed Tape - profiled	< 1.0
8	Methyl methacrylate	< 1.0
9	Thermoplastics profiled	< 1.0
10	Polyurea	< 1.0
11	Cold applied plastics	< 1.0
12	Experimental	< 1.0
13	Green lite powder	< 1.0
14	Polyester profiled	< 1.0
15	Tape removable	< 1.0
16	HD-21	< 1.0

[Adapted from Migletz and Graham, 2002]
[Highlighted materials are currently in use in NC]

Some state departments of transportation are leery of collecting quantifiable measurements of the condition of public infrastructure so as not to be exposed to tort liability [Baker and Lambert 2001]. Vereen noted the importance of measuring retroreflectivity in order to possibly mitigate potential civil claims against state departments of transportation. However, without a comprehensive plan to measure and maintain all roads cyclically, it may leave the departments of transportation open to higher liability in the interim. In other words it might be better not to do it at all from a lawyer's point of view. A record that the state knew that a certain road sign had a low retroreflectivity value is a plaintiff lawyers dream [Vereen et al 2004]. Collecting and analyzing data is a key step in developing performance based asset management strategies.

Pavement marking materials themselves provide a base line of retroreflectivity. However, the bulk of the retroreflectivity is achieved through the addition of glass beads embedded into the pavement marking material. Figure 2.1 illustrates the basic concept of retroreflectivity and shows how the light from a vehicle's headlights is retroreflected off of a glass bead in the pavement marking back to the driver's eye [ASTMa, 2005].

2.1.2 Retroreflectivity Measurement and Standards

The American Society for Testing Materials (ASTM) standard number E1710-05 describes the testing standards using portable retroreflective measurement devices to measure pavement-marking retroreflectivity, which is quantified by the coefficient of retroreflected luminance (R_L) in units of millicandles/m^2/Lux (mcd/m^2/lx) [ASTMa 2005]. Current ASTM standards require a specific geometry commonly called the 30-meter geometry, which is designed to measure the retroreflectivity at a point 30 meters ahead of a vehicle. This is believed to be the point at which most drivers observe the roadway at night. Figure 2.1 was adapted from ASTM E 808 and shows the basic geometry required to evaluate retroreflectivity at 30-meter geometry [ASTMb 2005].

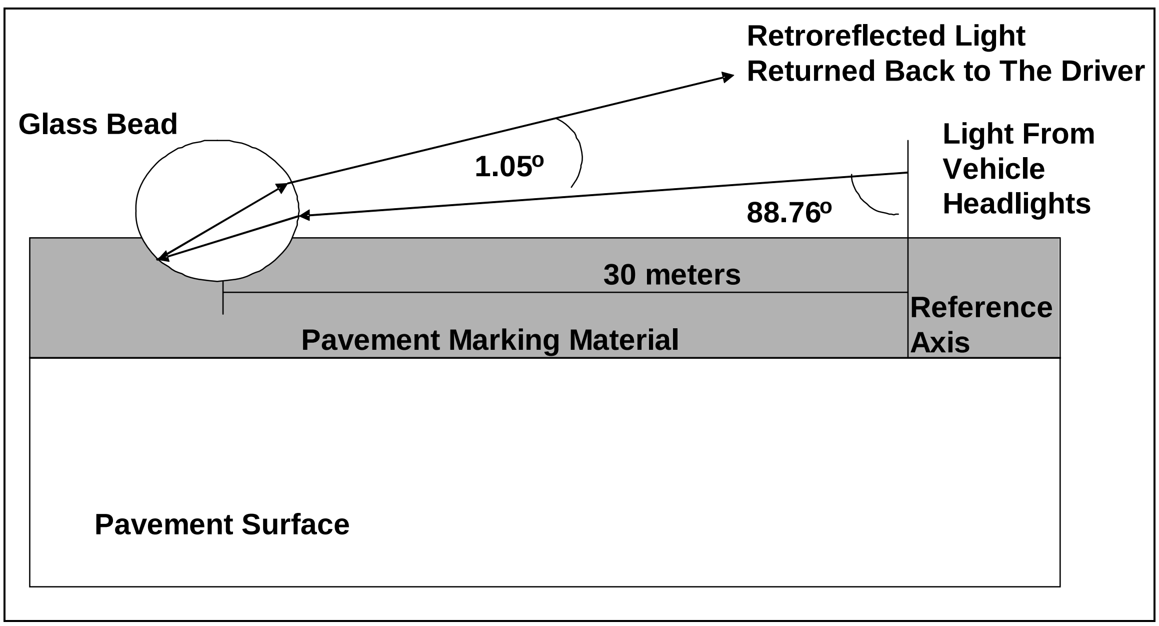


Figure 2.1. Basic Principles of Pavement Marking Retroreflectivity

A retroreflectivity test is conducted using a handheld measuring device, which directs light onto the pavement marking, and measures the amount of light reflected back into the device. Light is directed onto the pavement marking at an entrance angle of 88.76 degrees measured from the reference axis, which is the vertical line perpendicular to the pavement surface. The amount of reflected light is measured at an observation angle of 1.05 degrees, which is the difference required for light to reflect back from the headlight to the driver's field of vision based on a spot 30 meters in front of the driver's vehicle.

Additionally, ASTM E 808 requires that all new pavement-marking materials have a minimum retroreflectivity value of R_L equal to 250 mcd/m^2/lux for white markings and an R_L equal to 175 mcd/m^2/lux for yellow markings [ASTMb 2005].

2.1.3 Retroreflectivity Measurement Devices

Six retroreflectometers were evaluated by the Highway Innovative Technology Center (HITEC) and represent the six leading units used by transportation agencies [Texas Transportation Institute 2001]. Four of the six units were handheld devices and two were mobile units. All the units that were evaluated used 30-meter geometry to measure retroreflectivity. The Mirolux 12 was also evaluated but was left out of this summary because it uses 15-meter geometry, which is no longer acceptable under ASTM standards. The four handheld units evaluated were LTL 2000, MX30, MP-30, and FRT01. The two mobile units evaluated were the ECODYN and the Laserlux.

According to the HITEC summary, field tests verified that all six devices produce reliable results for measuring pavement marking retroreflectivity [Texas Transportation Institute 2001]. The HITEC evaluation indicated that each unit comes with different capabilities and transportation agencies should evaluate the cost verses capability before deciding on which unit would be best to purchase for that agency. Ultimately, any of the six retroreflectometers mentioned would produce viable results [Texas Transportation Institute 2001].

Handheld verses mobile collection methods each have advantages and disadvantages as well. The handheld units are inexpensive but require a large crew for safety reasons in order to collect a small number of samples. Mobile devices are significantly more expensive but provide for a safer collection method and can collect continuous data throughout the system at highway speeds.

South Carolina conducted statistical tests on handheld and mobile collection devices [Sarasua et. al. 2003]. The study evaluated handheld and mobile collection devices from a repeatability and reproducibility standpoint. The analysis found good correlation between handheld units. Additionally, the study concluded that although the fit was not as good between handheld units and the mobile devices that trends were still apparent. Specifically, the study concluded that both the handheld units and mobile device were capable of grouping retroreflectivity readings into low, medium, and high ranges. This was presented as a significant finding from a human factors stand point since slight variations in retroreflectivity is not noticeable to the driver [Sarasua et. al., 2003].

2.1.4 Types of Lane Markings

For the purposes of this study, edge lines are defined as either the white edge line found on the outer edge of both primary and secondary roads, or as the yellow edge line that is found in the middle of a divided primary road, usually marking a raised median. Center lines are defined as the white skip lines found dividing parallel lanes on a primary road or as the yellow skip lines or yellow center lines that divide opposing lanes on a secondary road. Figures 2.2 and 2.3 show the common lane marking systems for divided four-lane and undivided two-lane roads, respectively.

2.1.5 Previous Research

There are two previous studies that are closely related to this one. The first study was sponsored by the South Carolina Department of Transportation (SCDOT) and published in 2003. It dealt with pavement marking degradation and examined the effects of surface type, marking material, marking color, and maintenance activities on markings. The second study was conducted by the National Cooperative Highway Research Program (NCHRP) from 1994 to 1998. It examined long-term pavement marking practices from across the nation. Both of these studies are examined in detail.

2.1.5.1 South Carolina Study

SCDOT supported a research project at Clemson University and The Citadel to evaluate the effective life cycle of pavement marking retroreflectivity over time [Sarasua, et. al., 2003]. This study was a response to the need of SCDOT for a pavement marking management strategy based on material performance. Additionally, SCDOT felt that a better understanding of pavement marking management was needed in order to comply with the expected implementation of new FHWA pavement marking minimum retroreflectivity standards. Their primary research objective was to develop predictive models that could estimate the rate of pavement marking degradation. These models could then be applied to an overall pavement markings management strategy.

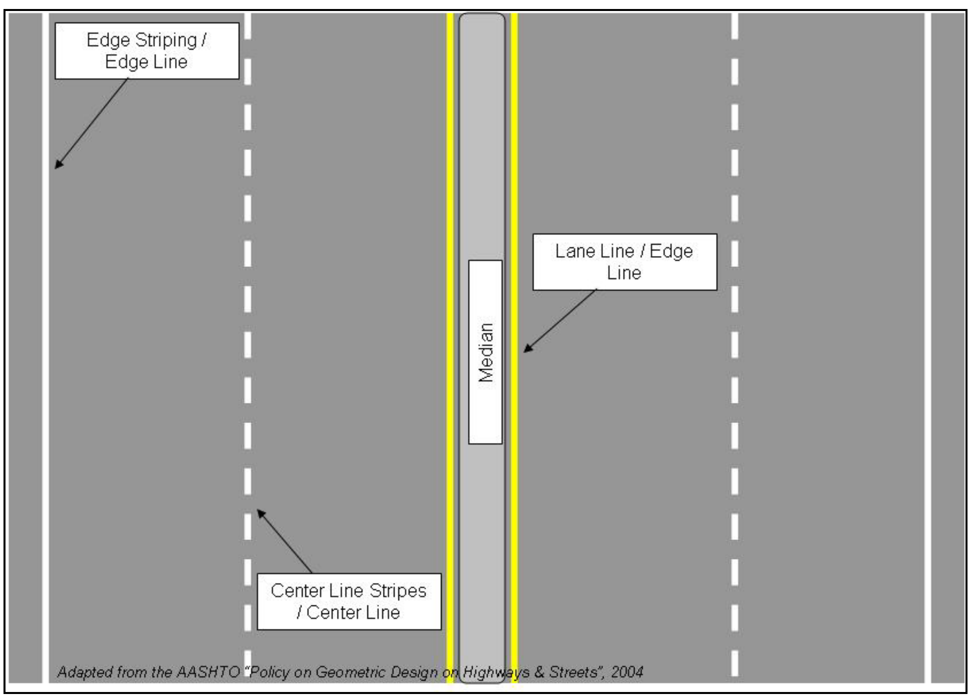


Figure 2.2. Pavement Markings on a Divided Four-lane Road

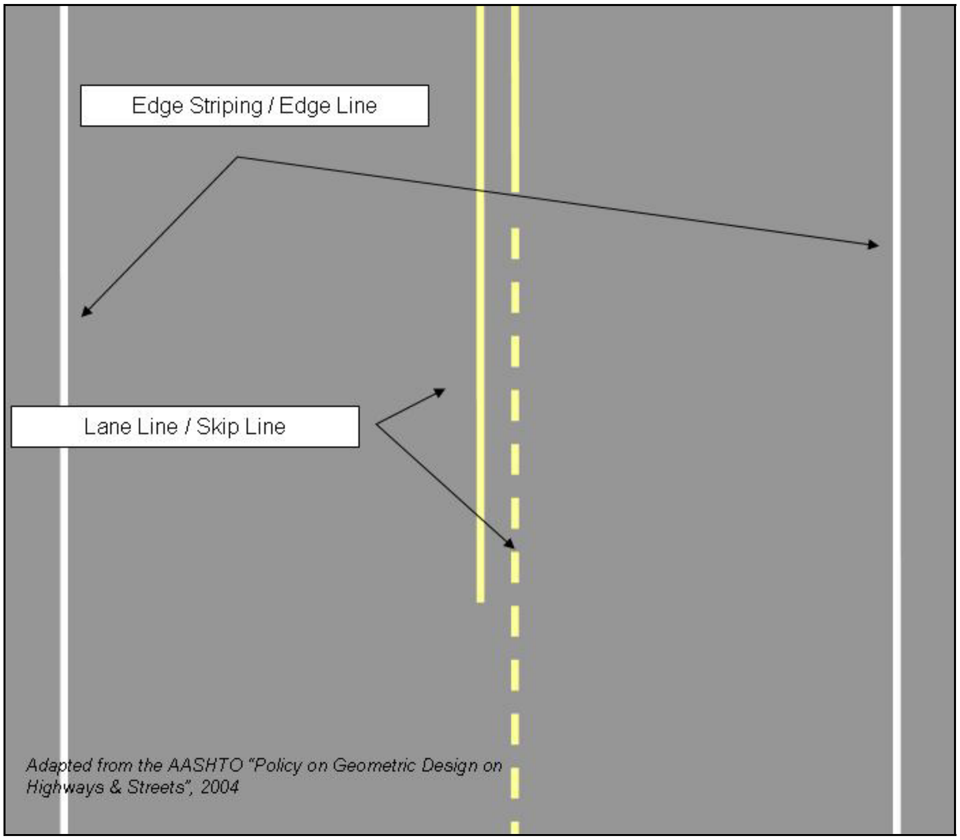


Figure 2.3. Pavement Markings on an Undivided Two-lane Road

The project focused on SC interstate highways and evaluated pavement marking retroreflectivity performance during a 28-month period. Data were collected 6 times during this period at over 150 sites throughout SC's interstate system. An average value was established for each time at each site from a series of 11 measurements taken with a handheld LTL-2000 retroreflectometer. Other retroreflectivity measurement devices were used during the research but only the data from the LTL-2000 were used in the analysis. Furthermore, researchers collected the data using a 30-meter geometry, as required in ASTM E 1710-97 [ASTMa, 2005].

During the data analysis portion of the research, retroreflectivity performance was determined using four major independent variables: surface type, marking material, marking color, and maintenance activities. Each variable was analyzed using regression analysis and was compared to the dependent variables. The dependent variables were the difference in R_L values between two successive time periods, and the percent difference between the two successive time periods. Using these as dependent variables helped to account for the large variation across the data set. Several other independent variables were considered but only these four were determined statistically significant in their effect on the performance of the pavement markings over time. Traffic volume was one variable that was initially thought to impact performance but was later determined not to.

Traffic volume was inversely correlated to the dependent variable of time and was adequately accounted for as time elapsed. Because time and traffic were directly related and traffic volumes remain relatively constant over the long term, traffic was accounted for in the time analysis. The analysis resulted in the development of three predictive patterns that demonstrate how SC interstate highway marking materials perform over time. All three patterns are shown in Figures 2.5, 2.6, and 2.7 below. Note that units are not specified in these figures. They are only intended to show the general nature of the curve.

The first pattern, shown in Figure 2.4, demonstrates that the retroreflectivity of new pavement markings increased non-linearly during some initial time period after installation [Sarasua et. al., 2003]. This was due to a greater number of reflective beads being exposed as the marking began to initially wear. After this preliminary time period, retroreflectivity was found to decrease linearly over time with a slight asymptotic curve at the end [Sarasua et. al., 2003].

The second pattern, shown in Figure 2.5, illustrates retroreflectivity degradation for existing pavement markings [Sarasua et. al., 2003]. The initial value of the retroreflectivity for existing pavement marking systems was typically lower than for new markings and there was a noticeable absence of the initial upward increase in retroreflectivity values.

Finally, the last pattern, shown in Figure 2.6, followed the same trends as the first two models but with a noticeable shift in retroreflectivity values that was caused by maintenance activity [Sarasua et. al., 2003]. The shift was observed in two different ways based on the type of maintenance activity performed. First, a re-striping maintenance activity would reset the retroreflectivity value back to the retroreflectivity value of a new marking and then the curve would follow the same trend as the first model. Second, snowplowing caused a noticeable shift downward in the curve at the time the snowplowing occurred but the curve maintained the same linear downward trend after the activity was finished.

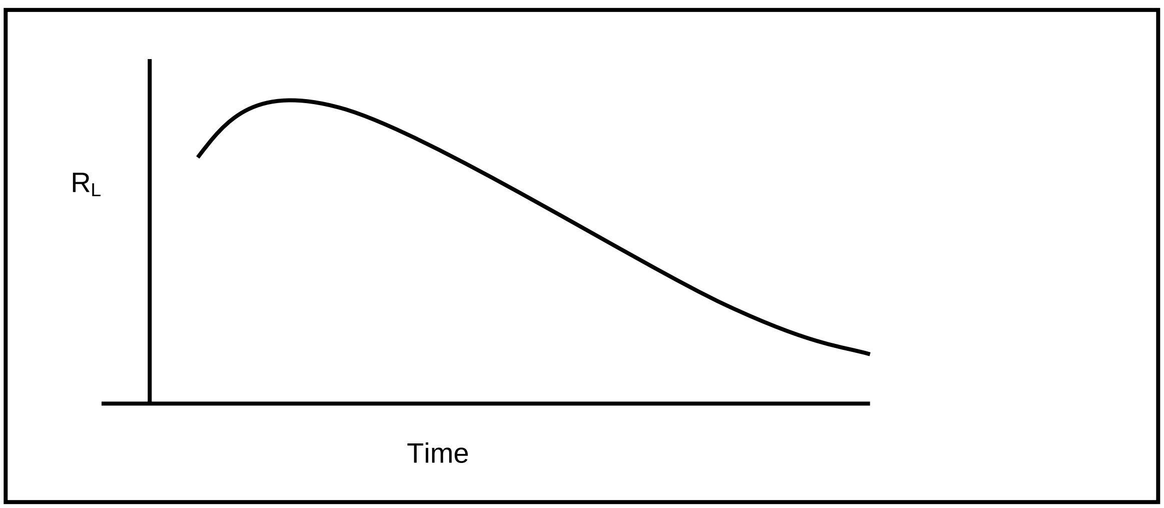


Figure 2.4. Predictive Trends for Newly Placed Pavement Marking

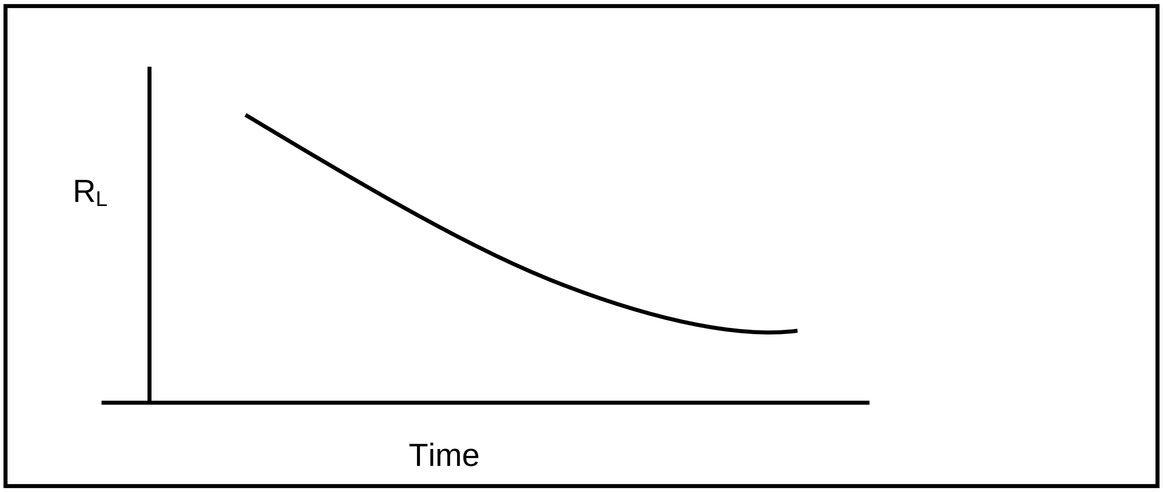


Figure 2.5. Predictive Trends for Existing Pavement Markings

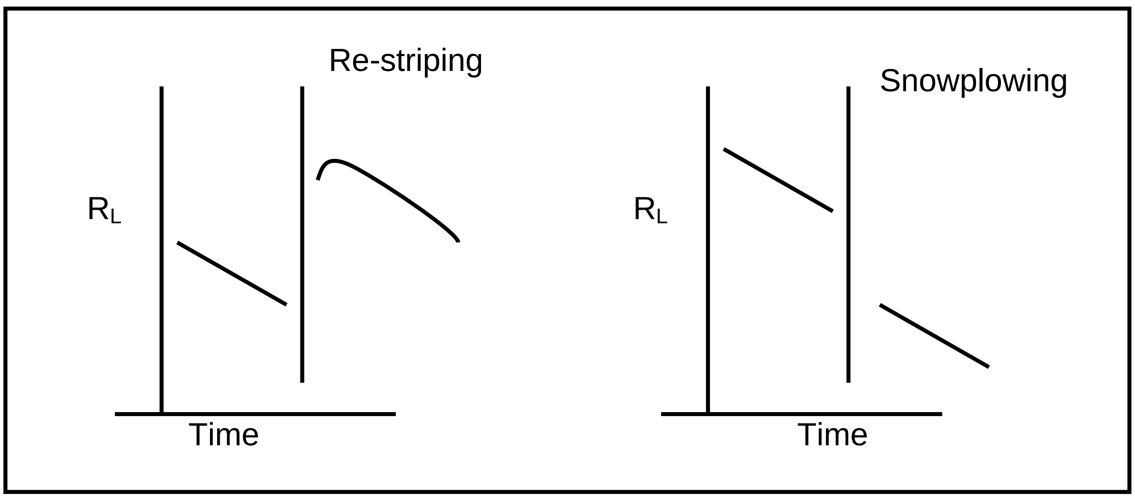


Figure 2.6. Predictive Trends for Remarking and Snowplowing

2.1.5.2 NCHRP Synthesis

The NCHRP synthesis study took place from 1994 to 1998 [Migletz, et al., 2001] and its purpose was to evaluate the life of durable pavement markings. Limited evaluations of some waterborne paints were included in the study as a benchmark. The study collected data on 362 longitudinal (edge, center, & lane) pavement-marking lines from 85 sites across 19 states. The study collected data on 13 thermoplastic sites and the lengths ranged from 1 to 50 miles.

The NCHRP study used regression analysis to evaluate various materials and establish a predictive degradation curve of the material performance over time. Marking material type, road surface type, and marking material color were the independent variables evaluated. These were the same variables addressed in the SC study. Only maintenance activities were omitted from the FHWA study.

Results from the regression analysis indicate there was a great deal of variation in identical materials at different sites. The variation was attributed to differences in roadway type, region of the country, marking specifications, quality control, and winter maintenance. However, no comments were provided regarding the current age of the pavement markings when the study was performed. Thus, no statistically valid conclusions could be drawn. Still, the analysis did indicate that yellow lines performed better than white. Migletz attributed this to the use of a lower threshold of material expectations rather than to superior performance. Table 2.2 shows as summary of the results of the Migletz study.

In a follow up study, [Migletz et. al. 2001] established a service life matrix that provides degradation rates sorted by cumulative traffic passages (CTP) and elapsed months. Table 2.3, is an adaptation of this matrix and shows the average service life for each material type in months. The matrix is sorted by line color and type of marking material and provides an average service life and standard deviation in months. Additionally, the matrix gives a service life range in months. There is a large amount of deviation in the average service lives of the materials listed. Since this data collection spanned 19 different states, this variation was a product of regional diversity in traffic and weather conditions.

Nationally, the two most commonly utilized pavement-marking materials are waterborne paints and thermoplastics. Paints make up approximately 60 percent and thermoplastics make up approximately 23 percent (total 83 %) [Migletz and Graham, 2002]. From Table 2.3 we see that the average service life for these is as follows:

- 10.4 months for waterborne paint
- 26.2 months for white thermoplastics
- 27.5 months for yellow thermoplastics.

Table 2.2 summarizes all of the key parameters and findings of the NCHRP study. In particular, the variability in service life was drastic, as one can see from table 2.3. The remaining findings have been discussed.

Table 2.2. NCHRP Study Summary

Objective	Develop retroreflectivity degradation rates for roadway pavement markings
Important Parameters	• Study was from 1994-1998 • Data were collected from 85 sites across 19 states • Used a mobile collection device (Laserlux with 30-m geometry) • Study focused on various durable pavement markings
Key Findings	• Large variations in the shape of the degradation curves • Regional changes influenced the shape of the curve for identical materials, and line type • Matrix of service life degradation rates established based on unpublished data • Average Life of waterborne paint is 10.4 months • Average Life of thermoplastics is 26.2 months • Average Life of polyurea is 24.7 months • Average life of epoxy is 23.0 months

[Migletz unpublished, 2000; Migletz et. al., 2001]

Table 2.3. Pavement Marking Accepted Service Life Matrix

Material	No of Pavement Marking Lines	Service Life In Elapsed Months		
		Average	Standard Dev	Range
White Lines				
Waterborne Paint	3	10.4	7.3	4.1 –18.4
Epoxy	18	23	17.1	1 - 56
Methyl methacrylate	7	14.4	7.6	6.8 – 29.3
Methyl methacrylate Profiled	9	21	13.4	7.8 – 43.2
Polyester	5	24.7	7.9	14.7 – 34.1
Polyester - Profiled	1	45.9	-	45.9 – 45.9
Thermoplastics	19	26.2	14.1	7.4 – 49.7
Thermoplastics - Profiled	14	23.8	12.8	4.7 – 55.7
Preformed Tape	11	27.4	13.6	11.7 – 60.0
Yellow Lines				
Epoxy	15	34.3	14.6	12.6 – 57.8
Methyl methacrylate	4	16.8	4.2	12.6 – 20.5
Methyl methacrylate Profiled	5	25.0	6.0	18.1 – 32.8
Polyester	2	43.8	5.8	39.7 – 47.9
Polyester - Profiled	1	39.6	-	39.6 – 39.6
Thermoplastics	10	27.5	12.1	11.0 – 41.6
Thermoplastics - Profiled	8	26.7	10.3	17.8 – 50.7
Preformed Tape	7	30.6	11.9	19.6 – 53.4

[Adapted from Migletz et. al. (unpublished 2000), test without roadway lighting and raised retroreflective pavement markers]

2.2 Methodology

This section presents the methodology used for data collection and analysis in this study. An independent contractor hired by the NCDOT to measure retroreflectivity for specified NC roads collected the data for this study. The available data set was reduced to only those roads that used thermoplastic pavement markings. Furthermore, for the initial analysis, only those roads that had been under observation for a full five years were used.

First, an average value analysis was used to establish the initial findings using both weighted and un-weighted averages. Second, an analysis of variance (ANOVA) was used to confirm these findings with a more sophisticated statistical test. The ANOVA test method allowed use of the data from roads that had not yet been observed for the full five-year period, thus giving us a larger sample set to analyze.

2.2.1 Data Collection

The NCDOT hired a contractor, Precision Scan LLC, to collect retroreflectivity data on specified NC roads using a mobile platform that could collect a large amount of data in a safe and efficient manner. The data were originally collected for quality control and quality assurance purposes to ensure the initial retroreflectivity values were as specified [McDiarmid, 2001]. The data collection effort took place from June 1999 through June 2006 and resulted in the collection of nearly 30,000 lane miles of data throughout N.C. Using the mobile device ensured that the data was taken over a broad portion of the road surface instead of just a single spot. NCDOT felt that eliminating the need for a technician to choose a specific spot, as is required with a handheld device, ensured that the collection remained objective.

The data collection device used in this study was a modified Laserlux mobile retroreflectometer mounted on a Chevy Suburban. Currently, ASTM standards are not published for measuring retroreflectivity using a mobile collection device but proposed methods are currently under review. In order to provide accurate readings that consider the current published ASTM standards, the contractor used an LTL-2000 handheld retroreflectometer and current ASTM procedures for handheld units in order to calibrate the Laserlux mobile retroreflectometer prior to each collection run. Each collection run consisted of a single road segment with segments being of varying lengths. Each segment was homogenous with respect to pavement marking material, material color, and road surface.

The retroreflectometer collected data using the standard 30-meter geometry by applying a 1/3 scale that measures approximately 10-m ahead of the vehicle. Figure 2.7 shows how a scanning laser measured a 42” wide swath that collected retroreflectivity values at a rate of 100 readings per second at a speed of 60 miles per hour. This equates to approximately 600 data points for a tenth mile road segment, which in turn translates to approximately 1 data reading for every 11 inches. The computer was set to collect values only within a given R_L range. This enabled the computer to recognize very large or very small values and remove them from the recorded data used to calculate the average retroreflectivity value for the road segment. An example of a low value would be from a section of unmarked pavement. The computer would recognize that this value is outside the preset range and discard it. Reflective raised pavement markers would be an example of something that would return an especially high R_L value and again the computer would discard this value as well.

The dashed lines in Figure 2.7 illustrate the collection path of the laser as the vehicle travels down the road segment (upward in the figure) and the laser sweeps across the pavement (shown as left to right in the figure) collecting retroreflectivity values. The dash lines are arced because the laser swings from one side to the other while the vehicle is traveling at highway speeds. The laser then resets and starts the next collection sweep from the same side proceeding in the same direction for each sweep.

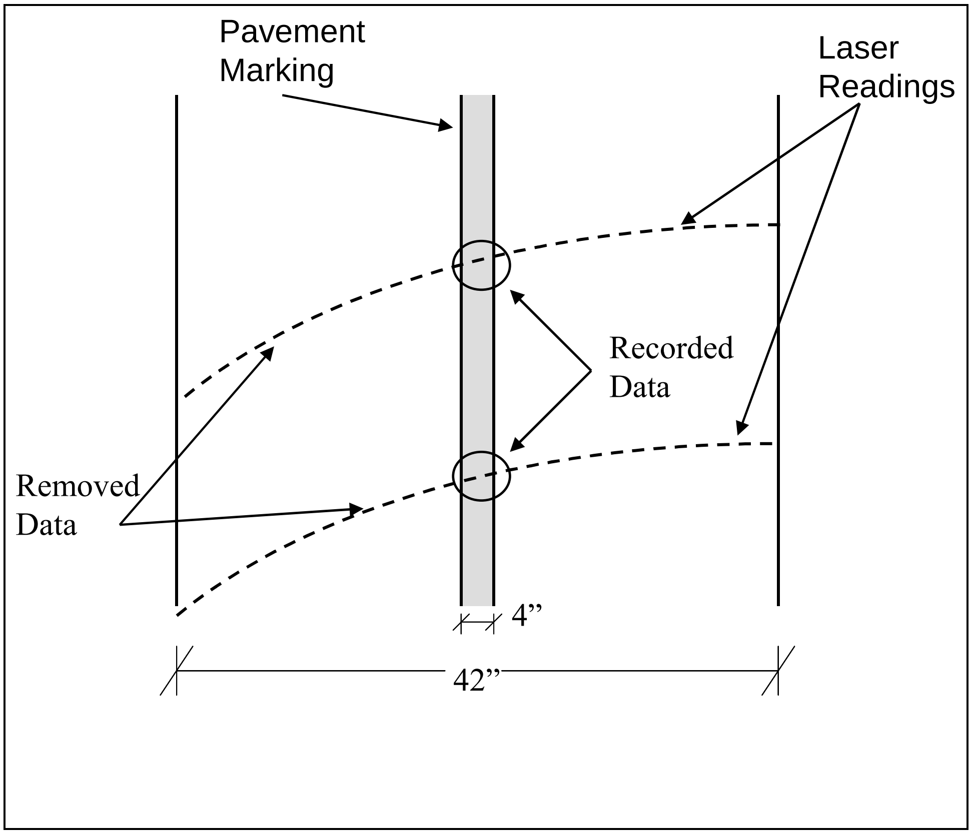


Figure 2.7. Data Collecting Laser

The R_L readings are averaged for every tenth of a mile and recorded into the onboard computer. Additionally, a continuous average was recorded throughout the entire roadway segment using all the valid data points that were determined to lie on the pavement marking. The R_L value has units of mcd/m^2/lx and is an average of all the valid scans recorded for a tenth-mile road segment. For a tenth-mile road segment there were approximately 600 data points evaluated but nearly 83 percent of the data are rejected because these values fell outside the preset range. This ensured only R_L values for pavement markings were recorded and not the background R_L for the road surface or for raised reflective pavement markers.

The vehicle was set up so that a single person can operate the vehicle and collect the data simultaneously. The operator was able to record any significant events using an event recorder that adds pre-designated codes to the data fields of the roadway segment. Significant events are those that might affect the meaning or interpretation of the data. Examples of event codes are roadway construction, intersections, or new paint. In addition to inputs from the Laserlux instrument and operator, a vehicle-mounted video camera recorded the entire data collection run for each segment. There is also a GPS device mounted in the vehicle and integrated into the onboard computer, which records the position data in the database at appropriate intervals.

Vehicle-mounted devices are subject to errors from variations in the suspension and roadway. However, the calibration process used throughout data collection minimized these precision errors. As part of a six-vehicle fleet, each LaserLux unit was calibrated on a known test bed of pavement markings at the fleet’s maintenance facility. The test bed was comprised of pavement markings with known retroreflectivity values that were calculated using the LTL-2000. Having a known test bed enabled the maintenance crews to calibrate each unit to a known standard as well as to each other. The calibration process accounted for errors due to changes in vehicle load, tire pressure, and ambient light.

The LTL-2000 was also used in the field during collection operations. During field collection, the technicians measured the retroreflectivity of the test section at random points using an LTL-2000 and then calibrated the mobile unit using that same test section with the known retroreflectivity. Daily calibration accounted for local climate changes and minimized errors that may result from temperature and humidity.

2.2.2 Data Reduction

For purposes of this study, a road segment is defined as a portion of a road of varying length on which the base material, pavement marking system, and marking color are uniform and continuous. Segments measured in this study varied in length from 4 to 50 miles. The retroreflectometer took continuous readings while the vehicle was in motion and filtered out any invalid readings. All valid readings were averaged for every tenth mile and the average value recorded in the database. An overall average was then computed for each road segment. Segments were measured initially within 30 days of application of the pavement marking, then again after six months, and finally one year after application. Further readings were taken annually for five years, so that there were seven data points between the initial observation and the five-year mark.

Due to the ongoing nature of the data collection, only some of the road segments had a full compliment of data and most roads had been under observation for some period less than five years. As will be discussed further below, this fact limited the options for statistical analysis. Data received from the NCDOT consisted of retroreflectivity measurement for over 800 road segments in NC.

Analysis was only conducted on those roads that used molten thermoplastic pavement markings. Molten thermoplastics is a long-life pavement marking material that is a blend of solid materials that become liquid when heated and then return to a solid state when cooled. While paints are the most common marking material in NC and elsewhere, they are considered to be non-durable. NCDOT uses an annual cycle for remarking with paint. This means most of these segments were repainted multiple times during the study. Since this study took measurements annually, the recorded data for painted markings was not used to model the degradation process. Painted markings need to be observed on a monthly basis for 12 months for valid data. Thus roads with painted markings were removed from the analysis and only thermoplastic markings were analyzed.

There were approximately 2,400 miles of measured roadway using thermoplastics markings for which data was available for study. Because thermoplastics are not commonly used on concrete, all of the road segments in this study had an asphalt surface course. Therefore, both marking material and pavement surface material were held constant during the analysis. Data were collected on both yellow and white colored pavement markings. Because these two colors have initial retroreflectivity values that are typically different and because they both degrade at different rates [Sarasua, et al], analysis was conducted separately on each color.

Lateral line locations were categorized as either center or edge lines. Centerlines include both center solid lines and center skip lines. To ensure valid conclusions, comparisons were only made between center and edge lines of identical color. Thus white edge lines were compared to white skip lines and yellow edge lines were compared to yellow centerlines.

2.2.3 Average Value Analysis

To conduct an initial analysis, the data set on thermoplastics was reduced to only those points that had a full five years of data available. This dramatically reduced the size of the data set, but still left enough road segments to conduct the analysis. The number of segments for which data was usable was as follows:

- Yellow center lines versus yellow edge lines (28 versus 8 road segments)
- White skip lines versus white edge lines (14 versus 6 road segments)

Even with the reduced data set, this still represented 419 miles of roadway with white markings and 210 miles of roadway with yellow marking. For each measurement time period (time = 0 to 5 years), the average R_L value was computed as:

$$RL_{ave} = [\sum (RL_i)] / [N_t]$$

where

RL_{ave} = average retroreflectivity for each time period in $mcd/m^2/lx$
RL_i = measured retroreflectivity of road segment *i* in $mcd/m^2/lx$
N_t = number of road segments measured for each category & time period.

A weighted average analysis was also conducted where the data was weighted based on the length of the road segment measured. Because the road segments did not have a uniform length, it is possible that the variation in segment length could skew the average value analysis. Road segments varied in length from 4 to 32 miles, with an average value of approximately 11 miles. The weighted analysis was conducted to determine if segment length affected the outcome of the analysis in any way. For each measurement time period (time = 0 to 5 years) the average weighted R_L value was computed using an weighted average value method such that:

$$RL_{ave} = [\sum (RL_i * L_i)] / [\sum L_i]$$

where

RL_{ave} = average retroreflectivity for each time period in $mcd/m^2/lx$
RL_i = measured retroreflectivity of road segment *i* in $mcd/m^2/lx$
L_i = length of road segment *i* in miles
$\sum L_i$ = sum of all road segment lengths in miles

2.2.4 Analysis of Variance

The average value analysis described above determined only that there may be a difference in the rates of retroreflectivity degradation based on lateral line location. But an ANOVA can accurately establish whether or not that difference is statistically significant. Analysis of variance (ANOVA) is a statistical procedure for determining whether the difference between two sample means is statistically significant. The procedure looks at the variance within the two populations to see if the difference between their respective means is due to normal variance within the groups or if it is due to a true difference between the two populations.

The null hypothesis (H_0) stated that the difference between the centerline mean and the edge line mean was statistically insignificant. The alternative hypothesis (H_a) stated that the difference in the means between centerline and edge line was statistically significant. A probability of F-value less than $\alpha = 0.05$ indicates that the null hypothesis should be rejected in favor of the alternative hypothesis and that the difference between the two means is statistically significant.

This approach was important because it allowed the use of all available data sets, not just those that had been under observation for five years. Due to the ongoing nature of the data collection activity, many of the road segments had been under observation for less than a full five years. Average value analysis as described above was only valid for comparing sets that had all been under observation for the entire time. ANOVA compares the data at a certain time interval to all the other data at the same time interval, allowing the use of road segments that had been under observation for less than a full five years to be studied. This meant that the sample size was different at each time interval and decreased as time went on.

Using all the available data on thermoplastic markings an ANOVA analysis was conducted at each time period for all data available at that time period. All the initial measurements (that is, time = 0) of yellow centerlines were compared to all the initial measurements of all yellow edge lines. Then the comparison was run at each successive time period using all available data in each time period. Because of the nature of the available data, the number of points analyzed was smaller in each successive time period. For both yellow and white markings, only about 25 percent of the total road segments had a full five years of data available. However, there were still enough road segments measured for a full five years that the results are considered to be sufficiently representative.

The ANOVA analysis used data from approximately 2,414 miles of NC roads out of a total of approximately 78,000 miles of primary and secondary roads. Thermoplastics markings are used on 22.7 percent of these roads, meaning that there are approximately 19,500 miles of road in NC marked with thermoplastics. Thus our sample size of 2,414 miles of road comprised approximately 12 percent of roads marked with thermoplastics. We consider this to be a sufficiently large enough sample size from which to draw our conclusions.

As previously mentioned, the road segments used for the study were not uniform in length, varying from 4 to 32 miles with an average value of 11 miles. To account for this variation, the ANOVA analysis was conducted a second time with values weighted according to the length of the measured road segment. This analysis was initiated to determine if there was any bias in the first ANOVA due to excessively long or short road segments.

2.3 Results

This section presents the results of the data analysis. Table 2.4 shows an overall summary of the statistics for all of the data points used in the analysis. Next, the average value results are shown and then followed by the ANOVA results. Finally, these results are compared to those reported in previous literature.

2.3.1 Overall Summary Statistics

Table 2.4 shows the overall summary statistics for the data collected, which are thermoplastics on asphalt. The first column is time given in months. Columns two, three, and four are the average retroreflectivity value, standard deviation, and range of values all given in mcd/m^2/lx.

Table 2.4. Summary Statistics for Thermoplastics on Asphalt

Time (months)	Mean R_L (mcd/m^2/lx)	Standard Deviation (mcd/m^2/lx)	Range of Values (mcd/m^2/lx)
0	365	103	168 - 563
6	324	82	201 - 473
12	319	85	163 - 488
24	235	75	110 – 443
36	212	67	93 - 383
48	223	62	88 - 364
60	222	75	98 - 389

2.3.2 Average Value Analysis (Un-weighted)

The un-weighted average value analysis showed that there was a difference in the degradation rates of center and edge lines for both white and yellow markings. Figure 2.8 and Table 2.5 show the results from the analysis of yellow thermoplastics. As expected both center line and edge line show an initial drop in retroreflectivity in the first two years and then show a much shallower, or even a flat curve beyond that. The two curves do not start at the exact same initial value due to the fact that they represent two averages of all centerlines and edges lines, and they are not matched pairs on the exact same group of road segments. The two curves are roughly parallel but the somewhat faster degradation in the centerline curve is visible. The third data series and trend line at the bottom of the chart shows the delta (difference) between the two average measurements at each time period. This trend line has a positive slope, indicating that the delta is increasing over time and therefore the two groups are degrading at different rates.

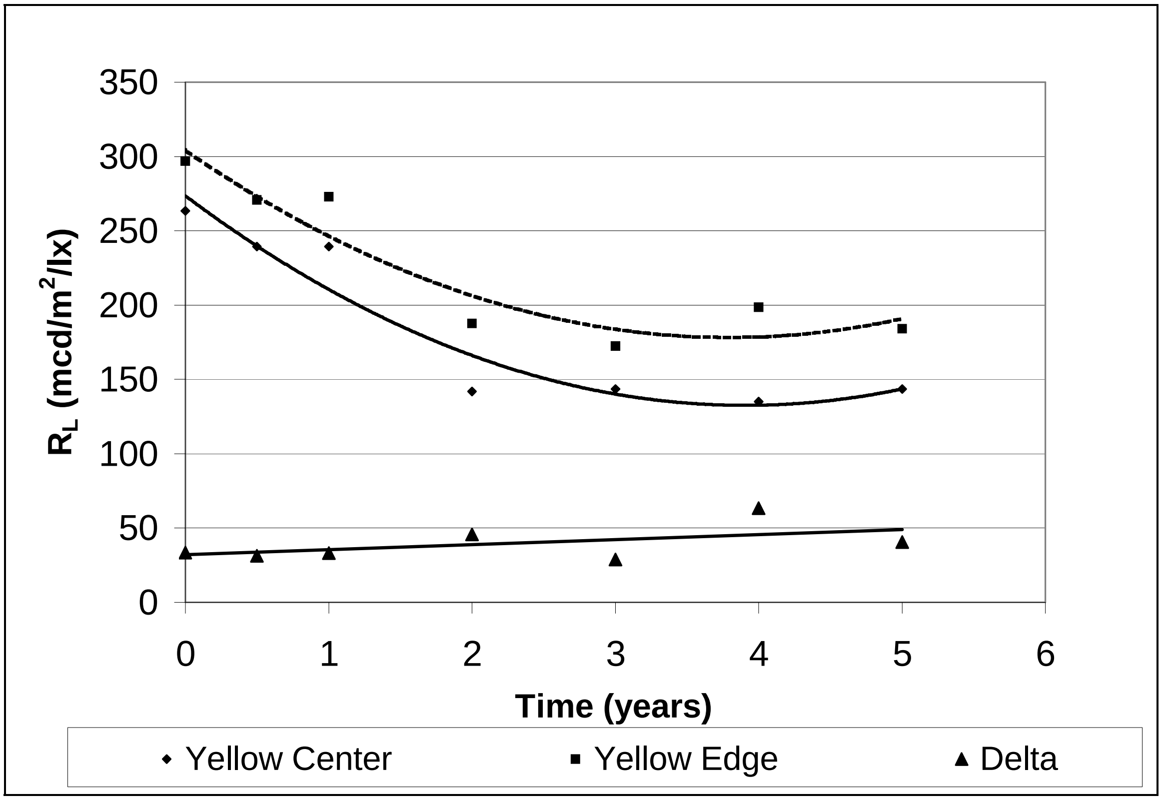


Figure 2.8. Average R_L Values Over Time of Yellow Thermoplastics (Un-weighted)

Table 2.5. Average R_L Values Over Time of Yellow Thermoplastics (Un-weighted)

TIME (years)	0	0.5	1	2	3	4	5
Yellow Edge	297	271	273	188	173	199	184
Yellow Center	263	240	240	142	144	135	144
Delta	34	31	33	46	29	63	41

***** Values given in mcd/m^2/lux***

The results from the comparison of white edge lines to white skip lines are shown in Figure 2.9 and Table 2.6. Similar to the yellow thermoplastics, the two curves show a difference in the rate of degradation, but this difference is more pronounced. In this case, the average value for white skip lines starts out higher than for edge lines at the initial observation, yet after five years the skip lines have a lower value, indicating a larger difference in degradation rate. The delta data series and trend line at the bottom of the chart shows the difference between the measurements at each time period. Similar to yellows thermoplastics, this trend line has a positive slope, indicating that the degradation rates between the edge and skip lines are different.

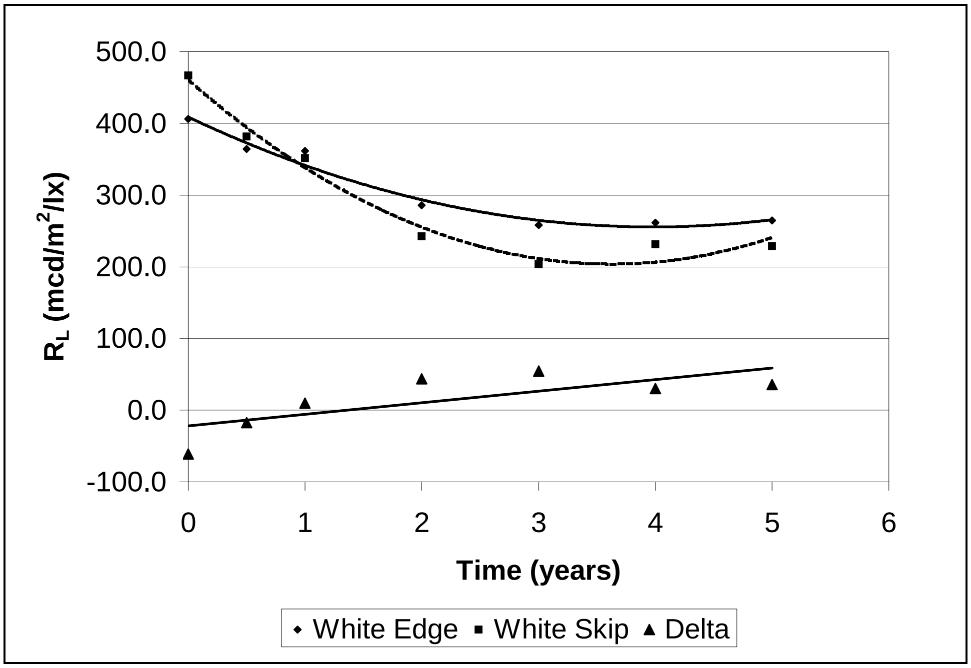


Figure 2.9. Average R_L Values Over Time of White Thermoplastics (Un-weighted)

Table 2.6. Average R_L Values Over Time of White Thermoplastics (Un-weighted)

TIME (years)	0	0.5	1	2	3	4	5
Yellow Edge	406	364	362	286	258	261	265
Yellow Center	467	382	352	242	204	231	229
Delta	-61	-18	10	44	54	30	36

***** Values given in mcd/m^2/lux***

2.3.3 Average Value Analysis (Weighted)

The weighted average analysis produced results very similar to the un-weighted analysis. Figure 2.10 and Table 2.7 show the retroreflectivity degradation of yellow thermoplastics weighted to account for variation in length of road segments. This curve is nearly identical to the un-weighted analysis for yellow thermoplastics shown in Figure 2.8. Both center and edge lines show an initial drop in retroreflectivity in the first two years of service and then exhibit a flat curve beyond that point. The delta data series shows the difference between two averages at each time interval. Its trend line shows a positive increase over time, indicating that the centerlines are degrading at a higher rate than the edge lines. Additionally, the weighted trend line shows a much steeper slope than the trend line in the un-weighted trend line in Figure 2.8. This means that the difference between the lateral locations is more pronounced in this analysis.

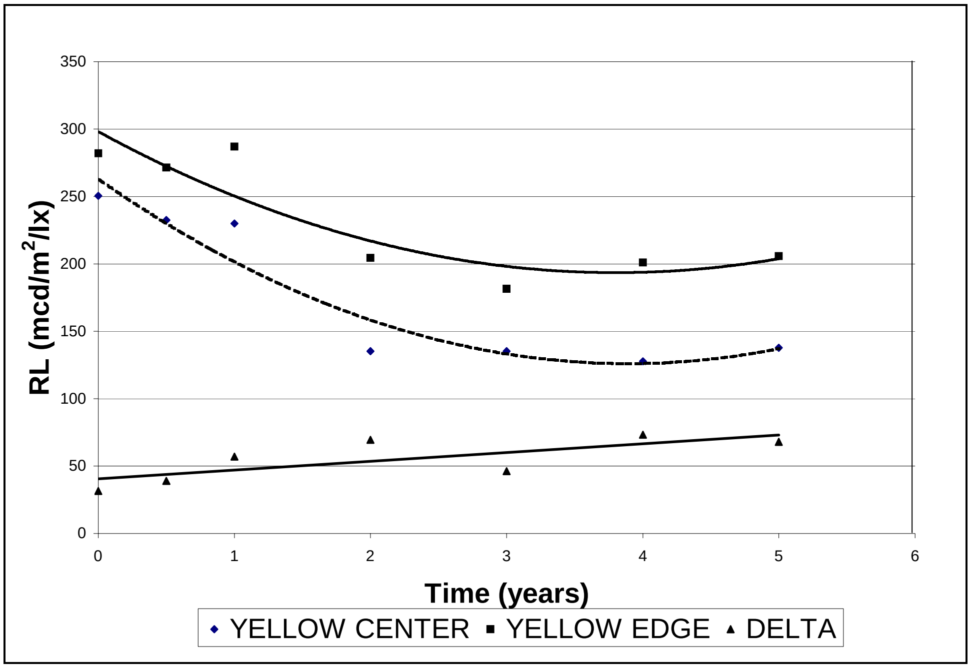


Figure 2.10. Average Value Over Time of Yellow Thermoplastics (Weighted by Length)

Table 2.7. Average R_L Values Over Time of Yellow Thermoplastics (Weighted by Length)

TIME (years)	0	0.5	1	2	3	4	5
Yellow Edge	282	272	287	205	181	201	206
Yellow Center	251	233	230	135	135	128	138
Delta	31	39	57	69	46	73	68

***** Values given in mcd/m²/lux***

Figure 2.11 and Table 2.8 show the retroreflectivity degradation of white thermoplastics weighted to account for variation in length of road segments. Again, this curve is very similar to the curves shown in the un-weighted analysis of white thermoplastics shown in Figure 2.9. Both skip and edge lines showed the initial drop in retro reflectivity in the first two years and then show a much shallower degradation rate. Additionally, as in Figure 2.9 the white skip lines starts with a higher initial average than white edge lines, but the two curves cross, indicating the skip line is degrading at faster rate than the edge line. Finally the trend line of the delta exhibits a positive slope, confirming that the skip line has degraded faster.

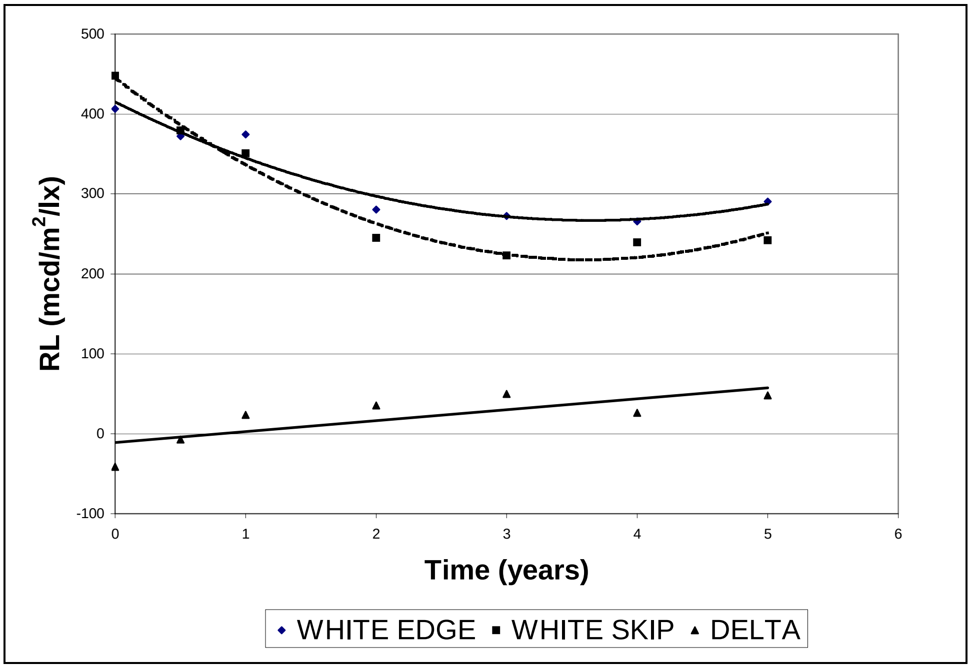


Figure 2.11. Average Value Over Time of White Thermoplastics (Weighted by Length)

Table 2.8. Average R_L Values Over Time of White Thermoplastics (Weighted by Length)

TIME (years)	0	0.5	1	2	3	4	5
White Edge	406	372	374	280	272	266	290
White Skip	448	379	351	245	223	240	242
Delta	-41	-7	24	35	49	26	48

***** Values given in mcd/m²/lux***

Both the un-weighted and weighted methodologies produced very similar results in this analysis. The two methods confirm the results of each other, and also indicate that weighting the data based on varying road segment has little effect on the outcome. For both colors, edge lines appear to degrade at a slower rate than center or skip lines.

The trend patterns seen in Figures 2.8 – 2.11 show a slight increase in retroreflectivity as the material aged. The trend patterns were shown to give the reader an indication of the gap between retroreflectivity at different lateral line locations. These figures do not show a pattern of degradation. The difference in retroreflectivity, as it relates to the lateral location, is the key trend of concern and clearly shows the gap increasing over time. This confirms that lateral location impacts the rate of degradation. The small upward trend seen in the pattern is most likely from variations in the data collection device.

2.3.4 Analysis of Variance (Un-weighted)

The ANOVA analysis was performed using the following null and alternative hypotheses:

- H_0 Null Hypothesis: The difference between the centerline mean and the edge line mean was statistically insignificant such that [R_L degradation of edge lines] = [R_L degradation of center lines] for all time periods.
- H_a Alternative Hypothesis: The difference between the centerline mean and edge line mean was statistically significant such that [R_L degradation of edge lines] ≠ [R_L degradation of center lines] for all time periods.

If the F-value from the analysis is less than or equal to the level of significance of $\alpha = 0.05$, this indicates there is sufficient statistical proof to reject the null hypothesis in favor of the alternative hypothesis. The results of the analysis are shown in Table 2.9. Values below .05 are highlighted in dark grey and those values between .05 and .1 are highlighted in light grey.

Table 2.9. ANOVA F-test results for white & yellow thermoplastics (Un-weighted)

	INITIAL	6 MONTHS	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
White Edge vs. White Skip Lines	0.5426	0.0001	0.0001	0.0003	0.0687	0.0778	0.0625
White Sample Sizes (Edge /Skip)	115 / 78	111 / 88	105 / 80	73 / 61	46 / 32	32 / 20	30 / 18
Yellow Edge vs. Yellow Center Lines	0.3718	0.1053	0.0875	0.0866	0.0595	0.0041	0.0529
Yellow Sample Sizes (Edge /Center)	59 / 37	59 / 38	55 / 36	47 / 16	29 / 10	20 / 6	18 / 6

Both comparisons show a statistically insignificant difference in the initial time period (0.5426 and 0.3718), as expected. Ideally edge lines and centerlines marked at approximately the same time would have similar R_L values. Since this is not a matched paired analysis (where we are comparing center lines and edge lines from the same road segment) it is expected that there will be some variation between the two population means. For white markings, there is an extremely significant difference between edge and skip lines between six months and two years (0.0001 to 0.0003). Because most of the degradation is expected to occur during this time period, it makes sense that these time periods would show the most significant difference in degradation. For three to five years, some of the values are out side of the 95 percent level of significance criteria (0.0625 to 0.0778) but remain close enough to indicate a high level of confidence that there is a statistically significant difference.

For yellow markings, the six-month comparison is just below the 90 percent confidence mark with an F-value of 0.1053. From year one through year three and again in year five, the F-values indicate that there is greater than 90 percent chance that edge and center lines have degraded at different rates. Year four exhibits a 99 percent certainty that the difference in the two group means is statistically significant.

2.3.5 Analysis of Variance (Weighted)

The ANOVA procedure shown above was repeated with the average values weighted according to the length of the individual road segments. The results of the analysis are shown in Table 2.10. Values below 0.05 are considered to be statistically significant and are highlighted in dark grey. Those values between 0.05 and 0.1 indicate a close proximity to the 95 percent level of confidence and are highlighted in light grey.

Table 2.10. ANOVA F-test results for white & yellow thermoplastics (Weighted)

	INITIAL	6 MONTHS	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
White Edge vs. White Skip Lines	0.0363	0.0035	0.0009	0.1383	0.1363	0.0738	0.0754
White Sample Sizes (Edge /Skip)	740 / 433	736 / 550	709 / 512	575 / 433	457 / 331	326 / 209	302 / 185
Yellow Edge vs. Yellow Center Lines	0.2828	0.1474	0.1126	0.0302	0.0143	0.0007	0.0032
Yellow Sample Sizes (Edge /Center)	415 / 184	434 / 180	412 / 174	371 / 116	308 / 86	209 / 58	185 / 59

The data for white thermoplastics indicate that there are statistically significant differences between the edge and skip line populations. The initial, 6-month, and 1-year periods have F-values less than 0.05, indicating the two populations are clearly different. It also shows very low F-values throughout the rest of the series, indicating an 85 percent or greater confidence level that the two populations exhibit a different rate of degradation. The low F-value at the initial reading is contrary to what we would expect, since ideally both the edge and center lines should have very nearly identical retroreflectivity values when the are first placed. However this analysis is conducted using two large populations, and this aberration is most likely due to normal variations in the two respective populations. As will be discussed in the recommendations, a matched pair analysis, comparing center and edge lines on the same road segment, would account for this variation.

Yellow thermoplastics also exhibit a statistically significant difference in degradation rates. As expected, the initial F-value is high, indicating that any difference between the two populations is due to normal variance within the populations. The F-value decreases steadily with time, and reaches the 95 percent confidence level at the 2-year through 5-year mark. This indicates that by year two, the edge and centerline populations are exhibiting clearly different rates of degradation.

2.3.6 Comparison to Current Literature

The degradation curves observed in this study generally follow those established in the South Carolina study as shown in Figure 2.6. The NCSU study curves do not exhibit the initial increase in retroreflectivity shown in the South Carolina curves. This is most likely due to the longer observation interval used in this study. South Carolina took monthly measurements for its test, whereas this study's data were collected at 6-month and 1-year intervals. It is likely the initial increases occurred but were no longer evident at the six-month mark.

The average length of service lives for thermoplastics in this study are longer than those estimated by Migletz, et al. all (2001). Migletz stated that the average service life for thermoplastics was a little over two years (See Table 2.3). However, all the road segments that were observed for five years in this study had a retroreflectivity greater than 100 mcd/m^2/lux and were still considered to be serviceable.

2.4 Conclusions

There is clear statistical evidence that shows a difference in the rate of retroreflectivity degradation between edge lines and centerlines for both yellow and white thermoplastic markings. The data was analyzed using four different methodologies, which all consistently showed a difference in the degradation rates between edge lines and center or skip lines. Both weighted and un-weighted average value analysis showed nearly identical results and indicated that edge lines degrade at a slower rate than center or skip lines for both white and yellow thermoplastics.

Additionally, both the un-weighted and weighted ANOVA analysis indicate that there is a consistent 85 percent or greater probability that edge lines and center lines degrade at different rates from six months through five years for both yellow and white thermoplastic markings. In most cases the level of significance is above 90 percent and reaches as much as 99 percent. For both white and yellow thermoplastics, the available data set supports the conclusion that centerline degrade more rapidly than edge lines from six months to five years. All four methodologies used to analyze the data are considered to be equally valid approaches. The fact that all four methods reached the same conclusion is a good indication that the conclusion is accurate.

All of the road segments observed for a full five years were still serviceable at the end of the observation period with an average retroreflectivity value above 100 mcd/m^2/lux. Formerly the service life of thermoplastics was thought to be approximately two years [Migletz et. al. 2001], but the data presented herein indicate that service life for NC may actually be much longer.

2.5 Recommendations

This study would suggest that a change in asset management practices by state departments of transportation might be in order. Because edge lines degrade at a slower rate than the centerlines or skip lines, there is a potential cost savings in replacing edge lines less frequently than center or skip lines. Discussions with NCDOT officials confirmed that typically a contractor will only lay pavement marking on a single lateral location at a time in a rolling operation, and must make multiple passes over the road to mark both edge and center lines. This means that the expense of mobilizing two separate times should not outweigh the savings of marking edge lines only half as often, especially considering that there are typically two edge lines for every center line for both primary and two-lane roads, which make up the vast majority of the road network in NC and elsewhere.

A second recommendation is that state departments of transportation should initiate well-designed and controlled studies of their pavement markings. The data available for the NCSU study was limited to pavement markings that have been under observation for five years or less. After five years of service, both yellow and white markings had R_L values in the range of 150 to 300 mcd/m^2/lux, which is still well above the proposed federal minimum standards. Several more years of data are needed to accurately determine the point at which both edge and centerlines will degrade beyond their useful service life. This recommendation would provide both NCDOT and other state transportation departments with valuable data for future study and maintenance cycle planning.

Data should also be collected in matched pairs in order to compare edge and center lines from the same road segment over the same period of time. This would eliminate variations in the data due to weather, traffic, and material installation quality. We also recommend that the observation interval needs be much smaller than the yearly measurements used in this study. Measurements should be made monthly or quarterly to more accurately model the degradation over time. Finally, since all available road segments were still serviceable after five years, the total observation time needs to be between five and ten years in order to accurately determine the end of service life of the thermoplastic pavement markings.

Because they make up approximately 60 percent of all pavement markings in NC and other places, it may be worthwhile to conduct a similar analysis on both waterborne and solvent paints. Because paints are considered to be non-durable and are typically replaced on an annual basis, this analysis would require that data be collected on a monthly (or more frequent) basis to accurately determine the degradation rate. This data could be used to determine what difference, if any, exists between the retroreflectivity rates of painted edge and center lines, and whether or not this difference warrants changes in asset management and maintenance schedules for these lines.

A final recommendation from this study is to develop a pavement marking experimental facility that could be used to support long-term study of different pavement markings in a controlled environment. Making observations monthly for several years to assemble an accurate mathematical model of the degradation curve could compare various types, or even all types, of pavement markings. In addition, random samples of actual markings on carefully selected support roads located through out a state could be collected to factor in regional weather effects and the average daily traffic volume.

3.0 THE IMPACT OF DIRECTIONALITY ON PAINT PAVEMENT MARKING RETROREFLECTIVITY

Water-based paint is currently the most commonly used pavement marking material. Paint is used on almost 60% of the total pavement marking mileages [Migletz and Graham 2002]. In North Carolina, water-based paint markings are reported to make up more than 80% of the total marking mileages [NCDOT 2008]. As a result, the primary focus of this study is on paint pavement markings. Normally, paint markings are applied on secondary routes where traffic volumes are relative low [NCDOT 2008]. This is because paint materials often have lower initial retroreflectivity values and degrade at a faster rate than other pavement marking materials. They are usually classified as non-durable marking materials [TxDOT 2004].

A congressional mandate, section 406 of the 1993 Department of Transportation and Related Agencies Appropriations Act, directed the Secretary of Transportation to revise the MUTCD to include a standard for minimum levels of retroreflectivity that must be maintained for traffic signs and pavement markings [Vereen et. al. 2004]. The minimum retroreflectivity levels and maintenance methods for traffic signs were published in revision 2 of the 2003 version of the MUTCD. The final rule has been effective since January, 2008 [FHWA 2008]. The Federal Highway Administration (FHWA) is working with other research agencies to establish a similar minimum retroreflectivity standard for pavement markings. The minimum retroreflectivity requirement for pavement markings is expected to be included in a future version of the MUTCD.

Concern about meeting future MUTCD minimum retroreflectivity levels led the North Carolina Department of Transportation (NCDOT) to initiate a research project to evaluate pavement marking material performances and service lives. The retroreflectivity directionality study reported herein is part of the overall research effort to evaluate paint marking performance on roads with low traffic volumes. While collecting field data on paint markings, the research team found that painted centerline pavement markings have significant directionality, which means the retroreflectivity values measured in one traffic direction are significantly different from the values measured in the opposite direction on the same segment of roadway. Since this finding could affect how public agencies respond to the new standards and how they maintain their markings, public works managers need to be aware of this phenomenon and its implications.

Sparrow pointed out that the new and recent legislation in the areas of transportation and environment has highlighted the need to incorporate a variety of previously extraneous factors into infrastructure decision marking [Sparrow 2001]. Paint marking directionality is one of those factors which public works managers normally do not attend to. However, when the FHWA publishes a minimum retroreflectivity requirement, it must be met.

Public works managers are also well aware of the need to achieve increasing infrastructure performance and productivity [Price 2002]. Performance standards for infrastructure systems describe the qualities needed by the owner, users, and other stakeholders [Switzer and McNeil, 2004]. This chapter provides some useful insight into this subject.

3.1 Research Objective

Paint retroreflectivity directionality is important because drivers experience different centerline levels of retroreflectivity in each travel direction. It is possible that the paint pavement marking retroreflectivity in one direction meets the minimum requirement while in the other direction it does not. The objective of this study was to investigate the retroreflectivity directionality property of paint pavement markings to find the relationship between the retroreflectivity values and the paint installation direction, to quantify these differences, and to determine whether retroreflectivity directionality could have an impact on paint markings meeting the pending FHWA minimum retroreflectivity levels.

3.2 Research Scope

The scope of this study is on the retroreflectivity directionality of paint pavement markings on two-lane highway centerlines. The data collection efforts were made on two-lane highways because two-lane highways comprise the majority of the highway system and traffic control for data collection (for safety) was much easier on two-lane highways than on other types of highways. In North Carolina, 74,015 of the total 79,042 roadway miles (93.6%) are two-lane highways [NCDOT 2007]. Since most two-lane highways were marked with paint pavement markings, NCDOT estimated that more than 80% of its total marking mileages were paint [NCDOT 2008]. This study does not address multi-lane roads or divided highways.

The centerline pavement markings were measured in both directions of traffic flow. The retroreflectivity values in each direction were averaged separately for each stripe. The centerline pavement markings did not provide the same retroreflectivity levels for each travel direction. Instead the average of all readings for each of the two directions (for each stripe) differ significantly.

The retroreflectivity values of edge pavement marking lines were measured in one direction because they are always painted in the direction of travel. Thus, driver always see the same retroreflectivity no matter which edge line is being considered.

Other types of marking materials with glass beads dropped on during installation (such as thermoplastics and epoxy) are known to have the same retroreflectivity directionality property as paint, but they were not investigated in this study due to the time and budget constraints of the project.

3.3 Background

Numerous papers and reports relevant to pavement marking research have been published in recent years. The congressional mandate to include the minimum levels of retroreflectivity in the MUTCD has given rise to a number of recent research efforts related to pavement markings. Various sources of information relevant to pavement marking studies were obtained and reviewed. A summary of the findings of these studies and sources is presented in the following paragraphs.

3.3.1 Paint Marking Material

Paint is the oldest and most widely used pavement marking material. Paint is mainly composed of finely ground pigments that are mixed into a resin or binder system. Various ingredients and additives are incorporated to obtain certain desired properties. A liquid (water or solvent) is added to the mixture to produce a material that is pliable by application equipment [VDOT 2008]. Paint can be classified into two broad categories, solvent-borne and water-based. Solvent-borne paint is also known as conventional paint. Both categories will be discussed below.

One NCHRP project reported that paint is associated with high Volatile Organic Compound (VOC) content [Andrady 1997]. A VOC is defined as any organic compound that participates in atmospheric photochemical reactions which have a negative impact on some aspect of the environment. The average VOC content of solvent-borne and water-based paints are 383 g/l and 84 g/l respectively [Andrady 1997]. The U. S. Environmental Protection Agency (EPA) published its initial standard with the goal of reducing VOCs in architectural coatings [USEPA 1998]. The standard also addressed paint pavement markings and specified that all types of pavement markings (including paints) are subject to a 150 g/l VOC content limit. The EPA did not completely prohibit the use of solvent-borne paint materials with high VOC content, but their uses are limited and are subject to container size restrictions. Most transportation agencies in United States have eliminated their use and replaced solvent-borne paint with water-based paint because of the VOC content limit requirement. Water-based paint is currently the most commonly used pavement marking material.

Paint markings are typically 15 to 25 mils (1 mil = 0.001 inch) in thickness when applied. Paint drying time depends on the thickness and the formulation. As a rule of thumb, a paint truck speed of 10-12 mph will result in a paint thickness of 15-18 wet mils without beads. Paint markings can last 3 months to 4 years depending on the geographic region, traffic volume, snowplow frequency, application quality, and other factors that influence both performance and durability. Paint markings last longer in the southern states where snowplowing does not impact marking performance. In northern states, paint markings deteriorate significantly faster over the winter due to the severe weather conditions and snowplow activity. Some northern states report that they restripe paint markings more than once a year [Hawkins et. al. 2006].

Traffic paint can be installed either using premixed paint or plain paint. Premixed traffic paint has glass beads mixed into the paint during the manufacturing process. Plain traffic paint, on the other hand, has no glass beads mixed in during manufacturing. Both premixed paint and plain paint have glass beads dropped on during application to provide immediate surface retroreflectivity in the finished product. Premixed traffic paint was once quite commonly used but due to equipment problems, crew downtime, special handing requirements, crew complaints, etc., most state highway departments have switched to plain traffic paints with drop-on glass beads [ITRE 1995]. For example, the NCDOT requires that glass beads be dropped (using a suitable pressurized means) into the wet paint as the paint is applied to roads [NCDOT 2006].

3.3.2 Pavement Marking Retroreflectivity

Pavement marking retroreflectivity is a term used to describe the amount of light returned back to a driver from a vehicle's headlight as it is reflected back from the markings. The reflected light provides the driver with information about the road (e.g. its center or its edge) and enables a safer drive at night. Thus, retroreflectivity is highly relevant to roadway safety. Retroreflectivity is represented by a measure referred to as the coefficient of retroreflected luminance (R_L), and is expressed in units of candelas per square meter per lux ($cd/m^2/lux$). The unit commonly used for pavement markings is millicandelas per square meter per lux ($mcd/m^2/lux$) because of the low values [ASTMb 2005].

Pavement marking retroreflectivity is achieved through the use of glass beads embedded partially in the surface of the marking binder material (e.g. paint). Using glass beads to achieve nighttime marking retroreflectivity has a long history and is now an accepted practice worldwide. Pavement markings without glass beads are nowhere near as visible at night. During daytime hours, a non-beaded pavement marking will display richer and more uniform color [VDOT 2008]. Still, a much greater quantity of light will be reflected back at night if the marking is applied with glass beads embedded in its surface. Figure 2.1 shows how glass beads reflect back light from a headlight. There are actually thousands of beads in each segment of beaded pavement marking.

The glass bead refractive index, their embedment, and their density all have impacts on the retroreflectivity values of the pavement marking as a whole. The amount of retroreflected light depends on these parameters and on the type of the glass beads. The refractive index is determined by the chemical and physical makeup of the glass material [VDOT 2008]. AASHTO standard M247-07 requires glass beads to have a refractive index of 1.50-1.55 [AASHTO 2007]. Glass beads are recognized to provide their best retroreflection when about 40% of each bead is exposed above the marking and 60% is embedded in the marking. The Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FP-03) specifies the glass bead application rate to be 6 lb/gal or 12 lb/gal for waterborne paint depending on the type of glass bead used [FHWAb 2003]. This application rate generally provides a density that results in an optimal number of beads to always be exposed at this 40/60 rate.

3.3.3 Paint Application

In this section we described the typical paint application practices in use by the NCDOT. Readers should note that while these are relatively standard practices, other transportation agencies may have minor differences in painting operation details. The NCDOT is divided into 14 divisions. Each division typically has one paint truck (one division has two). Figure 3.1 shows one of those paint trucks. Each paint truck requires 4-5 crew members to operate. The paint truck can hold 210 gallons of paint materials in each of two tanks. One tank contains white paint and the other contains yellow paint.

Figure 3.1. NCDOT Paint Truck

Paint materials supplied by a manufacturer are usually made available in 30-gallon cans so a paint truck can hold 14 cans of paint in both tanks. Normally 210 gallons of yellow paint is enough for one day to apply but about 400 gallons of white paint are needed. Thus several extra cans of white paint are carried to the field in another truck and at some point during the day need to be added to the white tank. It should be noted that the same paint (supplied by N. C. Department of Correction) is used in all the divisions throughout the state. Thus, there should generally be excellent uniformity in paint materials used statewide by NCDOT personnel.

On two-lane highways, the centerlines are striped in one of the three patterns. Figure 3.2 illustrates the three patterns − two solid lines, one solid line and one skip line, or one skip line only. The striping work on a two-lane road consists of two runs of a paint truck. One run paints the yellow center lines and one white edge line, which is illustrated by direction 3 in Figure 3.2 (a). The other run paints the last (other) white edge line, which is shown as direction 4 in Figure 3.2 (a). The key question is whether the paint striping direction is related to the retroreflectivity directionality. In other words, if the paint striping direction is same as that shown in Figure 3.2 (a), we want to know if the retroreflectivity values measured in directions 5 and 7 are higher than, the same as, or lower than in directions 6 and 8.

3.3.4 Driver Line of Sight

Figure 3.3 shows the vehicle travel, paint application and driver line of sight directions. Figure 3.3 (a) illustrates the driver line of sight in one direction and Figure 3.3 (b) illustrates the other direction. In Figure 3.3 (a), the driver line of sight direction 9 is same as the paint striping direction 3. In Figure 3.3 (b), the driver line of sight direction 10 is opposite to the centerline paint striping direction 3. If the R_L values measured in the directions 9 and 10 are different for the centerlines, the drivers in the directions 1 and 2 would perceive different levels of retroreflectivity for the same centerline.

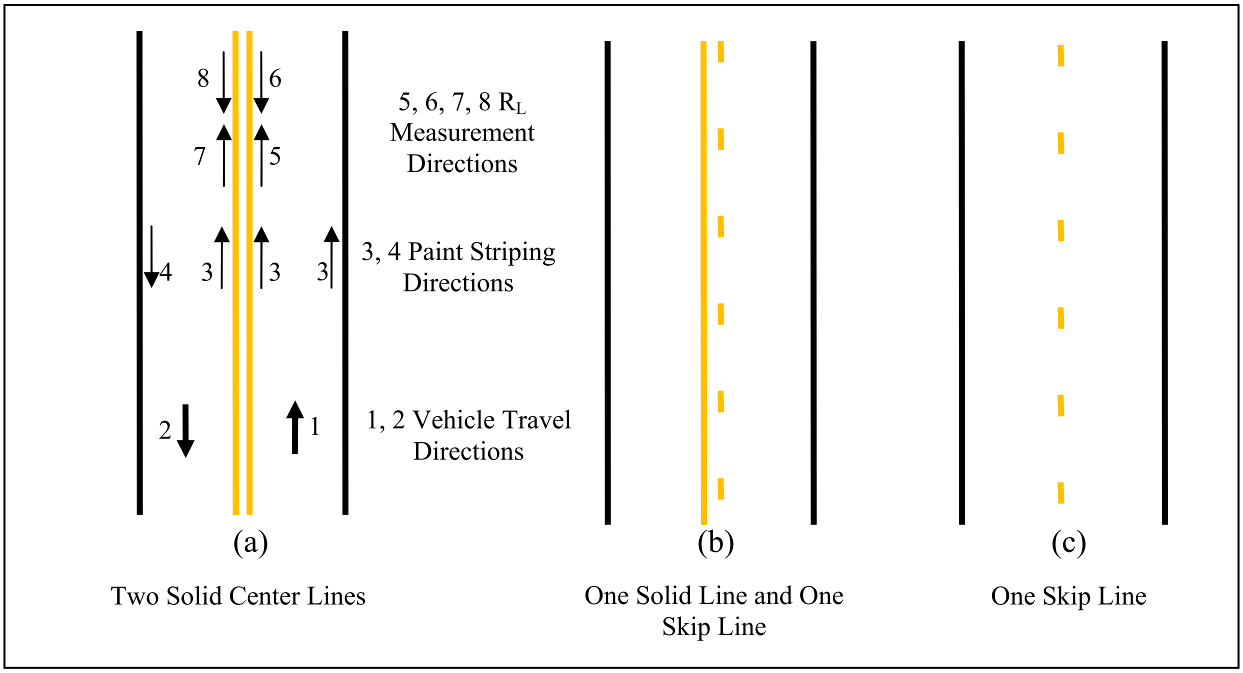


Figure 3.2. Vehicle Travel, Paint Application, and R_L Measurement Directions

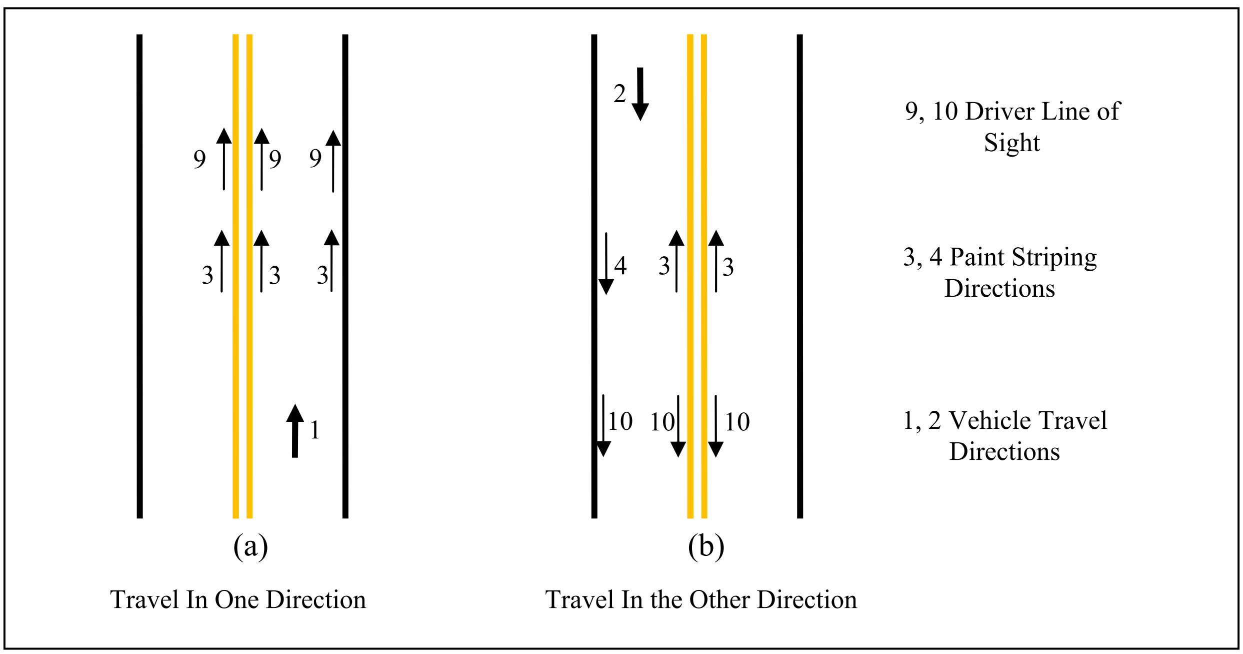
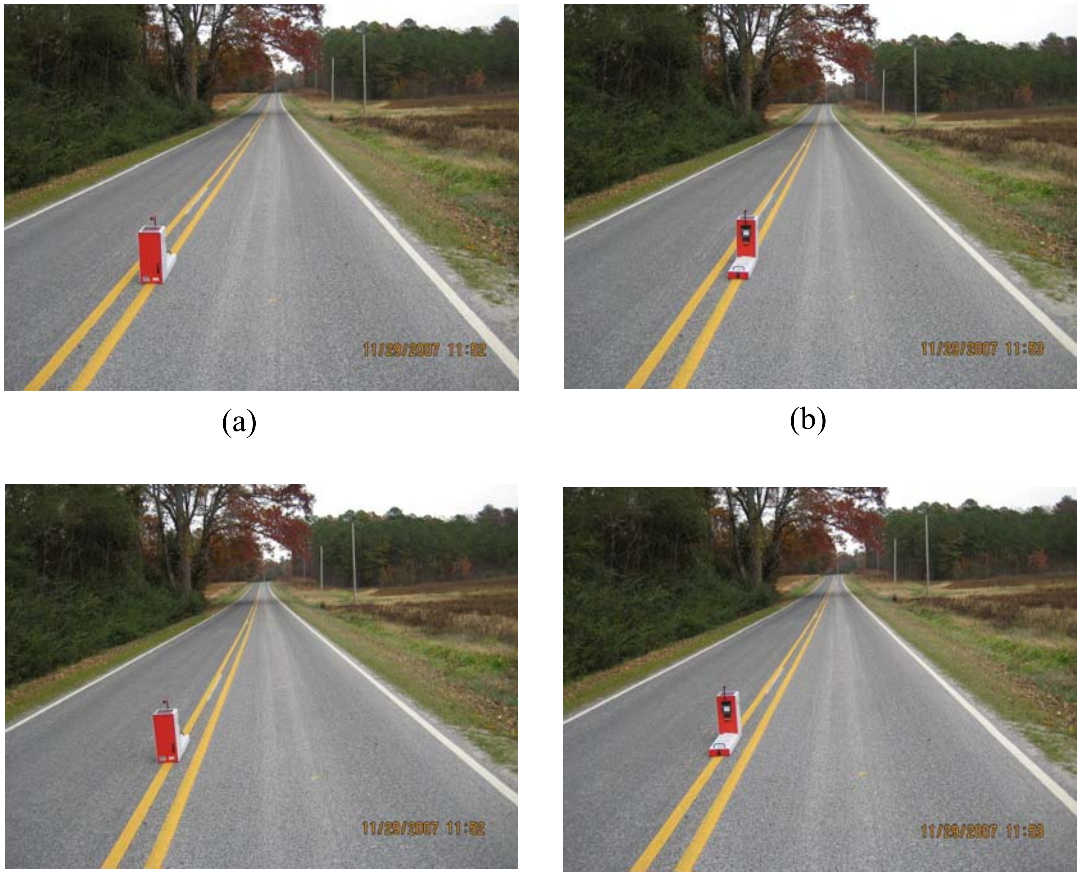


Figure 3.3. Vehicle Travel, Paint Application, and Driver Line of Sight Directions

3.3.5 R_L Measurement Directions

R_L values are measured in two directions for each centerline on two-lane roads. Figures 3.4 (a) and (b) show the R_L measurement directions for one centerline. Figure 3.4 (c) and (d) show the measurement directions for the other centerline. The measurement directions in Figure 3.4 (a), (b), (c), (d) correspond to the direction 5, 6, 7, 8 in Figure 3.2 (a).



(a) (b) (c) (d)

Figure 3.4. Retroreflectivity Measurement Directions*

* The retroreflectometer directions in Figure 3.4 (a), (b), (c), (d) correspond to directions 5, 6, 7, 8 in Figure 3.2 (a).

3.3.6 Retroreflectivity Directionality Explanation

The hypothesis that explains the directionality phenomenon is that glass beads have a horizontal velocity when sprayed from a pressurized dispenser, which causes more paint resin to cover one side of their surface than the other side. Figures 3.5 (a) and (b) illustrate an idealized paint application in which the glass beads are sprayed (or dropped) vertically into the paint resin. Alternatively, Figures 3.5 (c) and (d) show a more realistic painting scenario in which the glass beads have a horizontal speed when they are sprayed from a moving truck traveling at a speed of 10-12 mph. More headlight will enter and be retroreflected back from these glass beads in one direction than the other as is illustrated in Figure 3.5 (d). Thus, the retroreflectivity values measured in the paint truck striping direction are higher than the other direction.

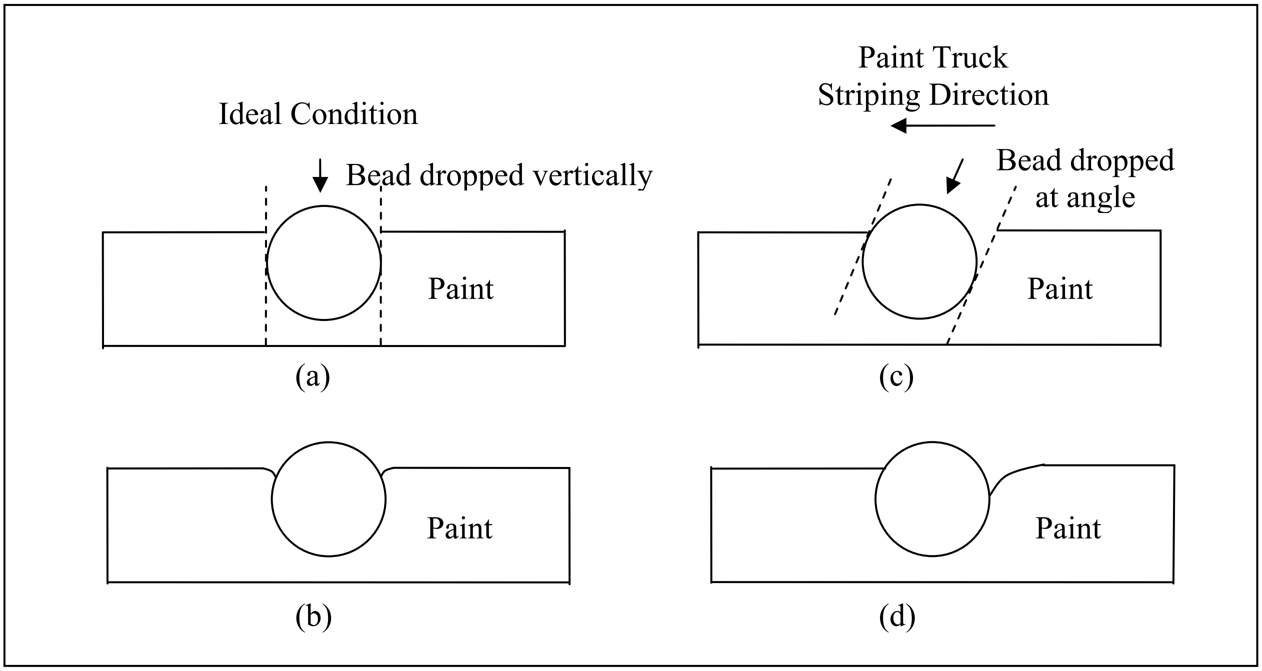


Figure 3.5. Bead Embedment Illustration

3.3.7 Data Collection Instrument

Two types of retroreflectometers can be used to measure pavement marking retroreflectivity values a handheld unit (or portable unit) and a vehicle-mounted mobile unit. Handheld and mobile collection instruments each have advantages and disadvantages. Handheld units have a lower initial cost, but require a large crew (for safety reasons) to collect a small number of samples. Mobile devices are significantly more expensive initially, but provide a safer collection method and can collect continuous data throughout the highway system at highway speeds.

ASTM has published a series of standards related to retroreflectivity measurement. The measurement geometry of the handheld instrument is based on a viewing distance of 30 meters with a headlight at the height of 0.65 meter over the pavement marking and the driver's eye at a height of 1.2 meters above the pavement [ASTMa 2005]. The entrance angle of the light into the glass beads is fixed at 88.76° and the observation angle is 1.05°. Figure 2.1 illustrates this retroreflectivity measurement geometry. The ASTM specification requires that a retroreflectometer uses a 30-meter viewing distance. Historically, 15-meter viewing distance instruments were developed and may still be used by some transportation agencies. Thus, when using retroreflectivity data made available by others, we must determine whether the instrument used to collect the data conforms to the ASTM specification.

A mobile retroreflectometer is capable of measuring pavement marking retroreflectivity while driving at highway speeds. Currently there are no specifications on using a mobile retroreflectometer to measure marking retroreflectivity values. A South Carolina study compared field data collected under various conditions and via several types of retroreflectometers. The study found good correlation between handheld units but the linear fit between a mobile Laserlux device and a handheld unit (LTL 2000) was not found to be as good as the fit between handheld to handheld instruments. Still, the readings made by the Laserlux and LTL 2000 generally fell within the same ranges [Sarasua et. al. 2003].

3.3.8 Data Collection Method

ASTM Specification E 1710-05 specifies a method of measuring pavement marking retroreflectivity using a handheld retroreflectometer that can be placed on the road marking. The standard requires that readings shall be taken for each direction of traffic and averaged separately for each of the yellow centerlines. The standard also requires that the average of the readings shall be reported for each traffic direction for centerlines [ASTMa 2005].

A critical shortcoming of the ASTM E 1710-05 standard is that it does not specify the sampling method to be employed when using a handheld unit to measure retroreflectivity values. Instead, the number of readings to be taken at each test location and the spacing between test locations shall be specified by the user. The ASTM E 1710 recommends readers to use the sampling method in the ASTM Specification D 6359 [ASTMa 2005]. However, the ASTM D 6359-99 specification was withdrawn in December 2006 because the sampling methods were not being used [ASTM 2008]. Thus, there is no current specified standard sampling method when using a handheld instrument to measure retroreflectivity values. An Iowa study reported that they collect samples once every 5 miles, unless conditions change. Each sample consists of an average of 5 readings over a minimum segment length of 160 feet [Hawkins et. al. 2006].

3.4 Methodology

The methodology of this study was to collect field retroreflectivity values using a handheld retoreflectometer and compare the retroreflectivity values of each traffic direction for two-lane road centerlines. First, we collected data at test locations on 40 roads. The markings on those 40 roads were installed at different times ranging from about 1 to 23 months after marking installation. The paint striping direction on those roads were not observed. The results of the first study strongly pointed to directionality as a factor affecting retroreflectivity. Then, a controlled study was initiated to determine to what extend the paint striping direction influences the retroreflectivity. We observed paint striping operations in field and measured the centerline R_L values in each direction. The two studies were described in the following sections.

3.4.1 Unknown Striping Direction Study

The research team used a handheld LTL 2000 retroreflectometer for data collection. The LTL 2000 retroreflectometer uses 30-meter geometry, which is the geometry required by ASTM Specification E 1710-05. The standard operating procedure in the instrument manual was strictly followed during field data collection. Field calibration of the LTL 2000 on each site was conducted before measurements were taken. A Global Position System (GPS) device was used to record the coordinates of starting and ending points on each test location and the field team used a digital camera to photograph the measured markings.

The paint data were collected on the secondary roads in four divisions in NC. Those roads have low traffic volumes, with annual average daily traffic (AADT) on most roads at less than 4000 vehicles per day. All measured roads were two-lane highways with asphalt pavement surfaces. Included in the study were 40 roads which were painted in 2006 and 2007. Paint installation data were provided by the NCDOT before the field data collection effort was undertaken. The installation data that was given to us included the road name, length, paint installation date, starting point, ending point, and other related information. The roads were measured twice by the research team. These measurements were taken in November, 2007 and May, 2008. Each round of data collection took about two weeks.

The purpose of the data collection activity was to evaluate paint marking performances. The research team selected a test location of the road to be measured. Test locations were not selected where there were sharp horizontal or vertical curves, but were otherwise randomly chosen. Test locations were about 200 feet long. Twenty measurements, approximately evenly distributed along the 200 feet segment, were taken for each pavement marking line. It is necessary to average numerous instrument readings in each direction on each line to account for variability in retroreflectivity along a line. The centerlines were measured in each direction of traffic. The average of the 20 readings was reported separately for each traffic direction for centerlines. It is this average that we present in our tables (3.1-3.4) of results.

Table 3.1. Centerline R_L Readings for 35-73 Day Old Paint Markings

(Paint Striping Direction Unknown)

Days Since Installation	First Yellow Center Line			Second Yellow Center Line		
	Measurement Direction		Difference	Measurement Direction		Difference
	↑5*	↓6*		↑7*	↓8*	
35	192	167	25	194	164	30
45	106	93	13	145	131	14
49	146	133	13	124	100	24
49	160	103	57	166	100	66
51	208	190	18	140	130	10
52	157	138	19	99	94	5
52	174	160	14	199	180	19
58	205	212	-7	212	198	14
70	162	127	35	205	170	35
72	147	109	38	172	118	54
72	238	213	25	195	159	36
73	148	103	45	190	136	54
Average	170	146	25	170	140	30

* Measurement directions are illustrated in Figure 3.2 (a).

Table 3.2. Centerline R_L Readings for 190-273 Day Old Paint Markings (Paint Striping Direction Unknown)

Days Since Installation	First Yellow Center Line			Second Yellow Center Line		
	Measurement Direction		Difference	Measurement Direction		Difference
	↑5*	↓6*		↑7*	↓8*	
190	141	128	13	158	135	23
204	150	105	45	152	98	54
217	149	127	22	107	86	21
217	148	149	-1	212	181	31
223	196	182	14	199	185	14
224	195	175	20	213	195	18
224	155	114	41	199	160	39
225	113	77	36	111	78	33
226	159	101	58	144	101	43
226	178	149	29	214	193	21
227	134	87	47	138	92	46
229	97	76	21	110	93	17
243	90	79	11	116	100	16
245	83	48	35	93	54	39
245	103	90	13	109	89	20
249	102	62	40	124	69	55
249	124	76	48	128	70	58
253	117	92	25	92	77	15
253	137	109	28	185	166	19
273	150	111	39	118	94	24
273	138	127	11	124	108	16
Average	136	108	28	145	115	30

* Measurement directions are illustrated in Figure 3.2 (a).

Table 3.3. Centerline R_L Readings for 518-696 Day Old Paint Markings (Paint Striping Direction Unknown)

Days Since Installation	First Yellow Center Line			Second Yellow Center Line		
	Measurement Direction		Difference	Measurement Direction		Difference
	↑5*	↓6*		↑7*	↓8*	
518	69	46	23	59	44	15
538	143	103	40	120	88	32
550	101	98	3	120	91	29
569	92	64	28	86	61	25
632	116	82	34	142	123	19
675	107	54	53	85	50	35
678	65	58	7	87	75	12
695	118	110	8	93	91	2
696	126	99	27	112	97	15
696	155	130	25	145	129	16
Average	109	84	25	105	85	20

* Measurement directions are illustrated in Figure 3.2 (a).

Table 3.4. Centerline R_L Readings for 14-22 Day Old Paint Markings (Paint Striping Direction Known)

Loc. **	Days Since Installation	First Yellow Center Line			Second Yellow Center Line		
		Measurement Direction		Difference	Measurement Direction		Difference
		↑5*	↓6*		↑7*	↓8*	
1	19	212	136	76	181	114	67
2	19	230	152	78	226	142	84
3	18	190	135	55	153	89	64
4	19	232	156	76	214	119	95
5	22	192	126	66	134	82	52
6	14	235	159	76	231	147	84
	Average	215	144	71	190	116	74

* Measurement directions are illustrated in Figure 3.2 (a).
** Locations are shown in Figure3.6.

3.4.2 Data Analysis

Tables 3.1-3.3 show the centerline data from the 40 roads that were measured but the paint striping direction was unknown. The direction numbers in Tables 3.1-3.3 correspond to Figure 3.2 (a). The ages of the markings are listed in the first column. The R_L readings for each line in each direction are shown in columns 2, 3, 5, and 6. The differences between readings in each direction for each line are shown in columns 4 and 7. The data are sorted by the age of the markings.

In Tables 3.1-3.3, the R_L values measured in one direction for both centerlines (directions 5 and 7, directions 6 and 8) are close to each other. The R_L values measure in two directions for the same centerline (directions 5 and 6, directions 7 and 8) are different, which is the paint pavement marking retroreflectivity directionality property we investigate in this chapter. We used hypothesis tests to determine if the differences were statistically significant.

Paired t-tests were used to test if the retroreflectivity differences measured in two directions are statistically significant. The null hypothesis is that H_0: The R_L mean values in two directional are equal. The alternative hypothesis is that H_1: the R_L mean value measured in one direction is larger than the value measured in the other direction. We used a one-tailed hypothesis test for this specific problem.

3.4.3 Known Striping Direction Study

In addition to the unknown striping direction study, an additional field study was conducted to investigate the relationship between the paint striping direction and retroreflectivity. We worked directly with a NCDOT paint crew to identify the paint striping direction beforehand. First, the paint application and application direction were observed and recorded. Then, six routes were selected to measure retroreflectivity values just a few days after paint installation.

Figure 3.6 shows arterial roads (e.g. NC 905, US 701) and secondary roads (e.g. SR1147) in the field study area. Thinner lines represent the state routes. Darker lines indicate the observed and measured road segments. The arrows in Figure 3.6 show direction of striping. The arrows correspond to the paint striping direction 3 in Figures 3.2 and 3.3. The numbers correspond to the first column in Table 3.4. Table 3.4 shows the collected data for this known striping direction study. The ages of the markings, the R_L measurements, and the differences between readings in each direction are shown in Table 3.4.

3.5 Results

We found that the centerline retroreflectivity values have obvious directionality, which means that the R_L values measured in one traffic direction were higher than the values measured in the opposite direction. The difference could be as large as 66 mcd/m^2/lux. Tables 3.1-3.3 show the yellow centerline retroreflectivity data for the unknown paint striping direction study. The data were sorted by the age of the paint markings. The average directional differences are generally in the range of 20-30 mcd/m^2/lux for the paints that are 35 to 696 days old. This represents between 15 and 30% more retroreflectivity in the painted direction than in the reverse.

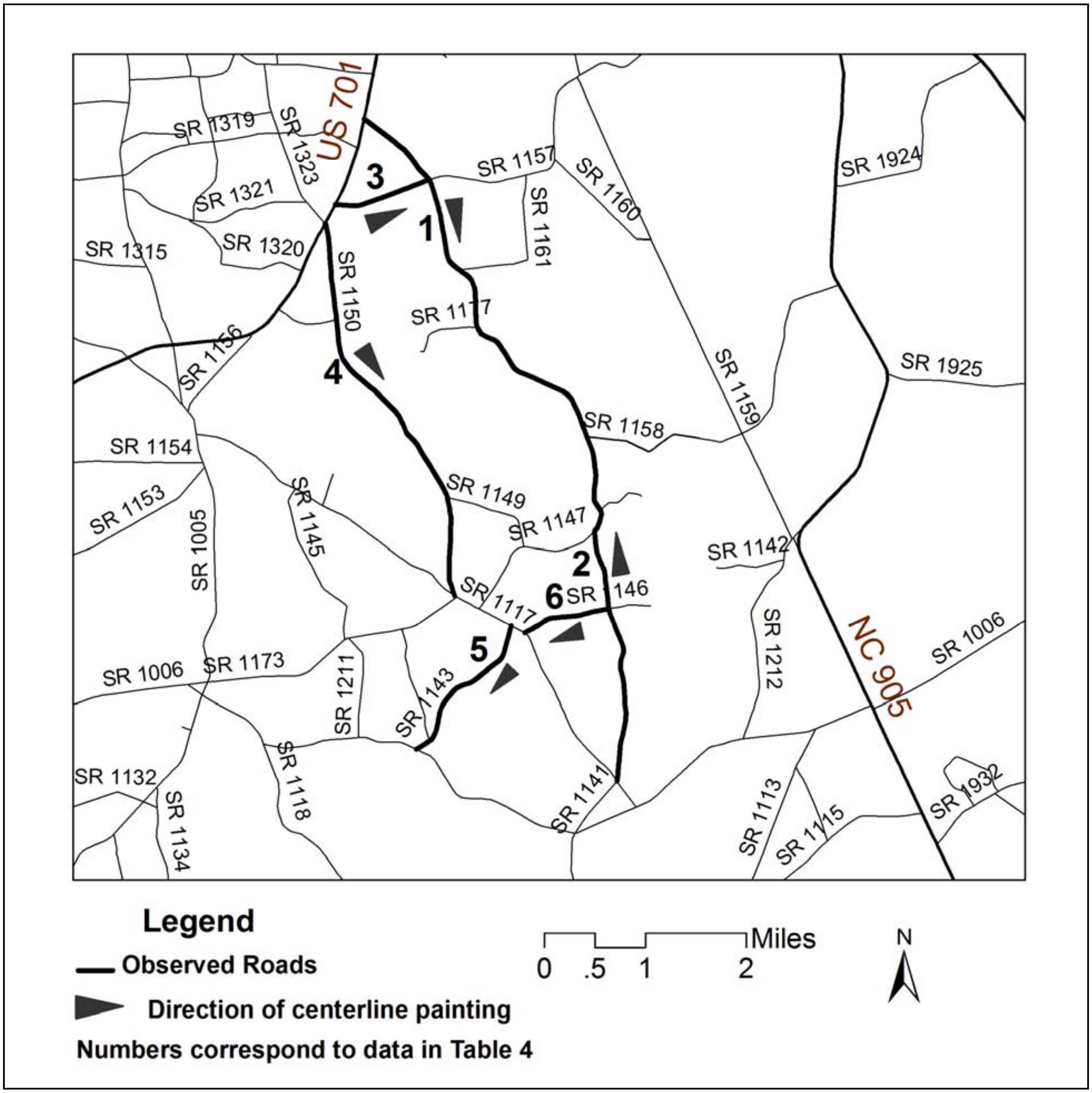


Figure 3.6. Directionality Data Collection Map (Columbus County, NC)

The mean values for each direction are 141 and 114 mcd/m^2/lux for the data collected in the four divisions. The t-test hypothesized mean difference is 0. The one tailed p-value is 6.09×10^{-28}. We specified the significance level $\alpha = 0.05$. We can reject the H_0 since the p-value is less than α, which means that the R_L mean value measured in one direction is larger than the other direction at a 0.05 significance level.

The retroreflectivity readings from the known striping direction study are shown in the Table 3.4. The average R_L differences of the two yellow centerlines measured in two directions (directions 5 and 6, directions 7 and 8) are 71 and 74 mcd/m^2/lux. The retroreflectivity differences are larger in this known striping direction study than the first study. Here one direction is 50%

higher than the other. One reason for this significant difference is that new paint markings have higher directionality differences than the older markings. In this study the measurements were made within days of the paint application. This is a point at which markings generally exhibit their highest R_L values.

The overall result of this study is that paint centerline retroreflectivity values measured in the direction of paint striping are significantly higher than the values measured in the opposite direction. If the paint is striped in the pattern as shown in Figure 3.2 (a), the R_L values measured in the direction 5 and 7 will be significantly higher than the values measured in the direction 6 and 8. The differences are in the range of 20-30 mcd/m^2/lux for older paints. For newer paint markings, the differences can be as large as 95 mcd/m^2/lux based on our field data.

3.6 Conclusions

Tables 3.1-3.4 consistently affirm that retroreflectivity values on painted centerlines measured in the direction of the striping (painting) are significantly higher than the values measured in the opposite direction on two-lane highways. In reality we did not watch the painting process for the unknown striping direction study, but the research results are so strong that we actually can identify the striping direction from the analysis. For example, the R_L values measured in the directions 5 and 7 in Figure 3.2 (a) are obviously higher than the values measured in directions 6 and 8, leading to the conclusion that the paint striping direction is same as direction 3. The results from the known striping direction study enabled us to draw this conclusion.

The research result implies that drivers perceive different levels of retroreflectivity, for the same pair of yellow centerlines, while driving in different directions on two-lane highways at night. In the paint striping direction, the retroreflectivity values are higher than the other direction. This research result is consistent with the measuring requirement in the ASTM E 1710-05 that the average readings shall be reported for each traffic direction for centerlines. The ASTM data collection procedures should be followed when collecting retroreflectivity data on two-lane highway centerlines with a handheld retroreflectometer. What this study demonstrates is how to interpret and use that data.

Paint pavement marking directionality also has a significant impact on determining whether or not a centerline meets the pending FHWA minimum retroreflectivity standard. On two-lane highways with two yellow centerlines, it is possible that one centerline meets the standard while the other does not. The lower average retroreflectivity value for a yellow centerline, measured in the opposite direction from the direction of paint striping (measurements 6 and measurement 8 in Figure 3.2 (a)), should be used to compare with the future FHWA minimum standard to determine whether or not the centerline meets the standard. Both lines are compared with the minimum. This is because drivers in that direction experience lower marking retroreflectivity at night, but they do see both lines. We should not use the average value of the two directions to compare with the minimum standard because no drivers observe the centerline with the average retroreflectivity from both directions simultaneously.

The readers should note that the proposed FHWA standard does not specify a measurement protocol for determining if a line meets the new standard. The proposed standard merely specifies a minimum retroreflectivity value. This chapter provides both measurement and analysis protocols to determine how to meet the standard. It provides an important addition to the standard in that it demonstrates the significant impacts of directionality on retroreflectivity and explains how to account for this in meeting the requirement.

Transportation officials and policy makers must be aware of the issues noted herein in order to effectively manage their pavement marking assets. It is important to measure and collect data according to ASTM standards. It is then essential to meet the minimum requirement established by FHWA. This study shows how to determine the correct values to compare to the minimum. It also firmly quantifies retroreflectivity differences as a function of both paint application direction and travel direction for two lane roads with painted pavement markings. It is highly recommended that a similar study be conducted for thermoplastics as well. This study addressed paints because they comprise the majority of markings on secondary roads.

One further question of interest, that could not be determined at the present time, is the persistence of the retroreflectivity difference over time. In the unknown striping direction study the range at which we collected data was generally between 1 and 23 months old. In the controlled study we collected data on essentially new markings. In a previous study we determined that paint markings should provide adequate performance for 2 years. Our future plans are to measure the controlled sites at a 2 year age. Doing so would bring closure to the work and would indicate what happens to retroreflectivity over the lifetime of a marking with respect to directionality.

4.0 THE IMPACT OF BEAD DENSITY ON PAINT PAVEMENT MARKING RETROREFLECTIVITY

Water-based paint is currently the most commonly used pavement marking material. Paint is used on almost 60% of the total pavement marking mileages according to a survey conducted in 2000 [Migletz and Graham 2002]. However, in NC at the present time, water-based paint markings are reported to make up more than 80% of the total marking mileages [NCDOT 2008]. Other types of pavement marking material such as thermoplastics, epoxy, polyurea, and preformed plastics are also used. The primary focus of this paper is on paint pavement markings though the research method presented herein can also be applied to other types of marking materials.

During daytime, drivers discern pavement markings mainly by the color contrast between the marking and the pavement surface. Nighttime visibility, however, is a function of the luminous contrast between the pavement markings and the road surface, which is generally determined by the pavement marking retroreflectivity. Retroreflectivity is a term used to describe the amount of light returned back to a source, such as the amount of light from a vehicle's headlight that is reflected back towards the driver. The reflected light provides the driver with roadway information and enables a safer drive at night. Retroreflectivity is represented by a measure referred to as the coefficient of retroreflected luminance (R_L), which is expressed in units of millicandelas per square meter per lux ($mcd/m^2/lux$) [ASTMb 2005]. The current ASTM standard requires that retroreflectometers use a 30-meter geometry [ASTMa 2005]. This article discusses retroreflectivity of pavement markings and its relationship to the beads embedded in the markings.

Pavement marking retroreflectivity is achieved through the use of glass beads on the surface of, and partially embedded in, the paint. Auto headlights are reflected in all directions when illuminated on markings without beads, and only a small amount of light is reflected back to the driver. In contrast, a much greater quantity of light is reflected back to the driver if the marking contains glass beads. Using glass beads in a reflective binder, such as paint, to achieve nighttime retroreflectivity is now a world-wide accepted practice.

Pavement marking retroreflectivity values are intuitively thought to depend on the quantities and qualities of the glass beads in the markings. However, if a glass bead is fully embedded in the marking binding material, it will not reflect headlight back to the driver. Retroreflectivity is primarily achieved by the portion of the beads exposed above the paint. Traffic engineers generally believe that an optimum occurs when 40% of each bead is exposed above the marking and 60% is embedded in the marking. In this paper, we define the bead density as the surface percentage of glass beads that are exposed above the marking binding material.

This paper reports on the use of image processing techniques to measure the bead density of paint pavement markings. Additionally we are reporting on a correlation study between painted pavement marking bead density and retroreflectivity.

4.1 Literature Review

Much pavement marking research to this point has focused on modeling of marking retroreflectivity and on the performance and the safety effects of pavement markings. Few articles examine why and how retroreflectivity values degrade over time. This paper examines one degradation factor – bead density.

. We reviewed several studies that provide insight into degradation models to predict long term pavement marking performance. An early study by Dale reported that pavement marking service life was a function of the type of pavement, the volume of traffic, and the average snowfall per year if the materials were applied to a properly prepared surface using the recommended application procedure [Dale 1988]. Several types of degradation models such as logarithmic [Andrady 1997, Abboud and Bowman 2002a], exponential [Perrin et. al. 1998], and linear regression models [Lee et. al. 1999, Sarasua et. al. 2003, Sitzabee 2008] were established based on the data collected in each of these studies.

The above mentioned studies have established that longitudinal pavement markings can reach the end of their service lives because of bead loss (resulting in poor retroreflectivity), loss of the marking material because of chipping and abrasion, color change of the marking, or loss of contrast between the base material of the marking and the pavement. Daytime and nighttime visibility are closely related because as a marking is chipped or abraded by traffic there typically is not only loss of marking material over time (which decreases the daytime visibility of the markings) but there is also a loss of beads (which results in a reduction in the nighttime retroreflectivity of the marking) [Migletz and Graham 2002].

Rich et. al. conducted a pioneering study of the impact of bead density on marking retroreflectivity [Rich et. al. 2002]. The study used a specialized digital camera (Spot RT) to collect high resolution glass bead images. The digital images were then converted into binary images. The binary images were analyzed to extract bead density values.

The Rich study found that the surface percentage of glass beads (bead density), glass weight percentage, and paint marking retroreflectivity variables were well correlated to each other [Rich et. al. 2002]. However, the work was preliminary and had three major shortcomings. First, the glass bead images used in that study were collected on roads with newly applied paint. The glass beads and the paint were in an initial perfect condition. There were no glass beads losses due to traffic wear, weather, or age. The elements on the images included both the glass beads and the background markings. However, pavement markings which have been worn by traffic normally show different patterns than newly applied smooth paint. In such markings there are numerous holes left in the paint as the glass beads are knocked out by wear and these were not accounted for in the Rich study. Also, the images used in the Rich study were taken from aluminum plates that were painted in the field and returned to the laboratory for evaluation [Rich et. al. 2002]. The images were not taken on real world pavement markings applied to asphalt. Finally, the details of the image processing procedure were not revealed in the available literature.

In another study conducted in Iowa, Mizera et. al. manually counted the number of glass beads in a 1 inch by 1 inch sample. Four samples were counted and an average value from four samples was calculated as the number of glass bead for the pavement marking line [Mizera et. al. 2009].

The objective of the Mizera study was to compare how many beads two bead guns dispense when operating at the same speed.

The goal of our study was to determine bead density, which was different from Mizera study. In a similar manual counting effort we found that the method cannot produce an accurate bead density value as we defined above. We describe the details of the manual count method in the Methodology Section of this paper and compare our results to Rich and Mizera studies.

4.2 Research Objectives

The first objective of this study was to find a way to measure the bead density of pavement markings in the field. The measurement method has two requirements. First, the method should be able to produce an accurate bead density. Second, the method should be easy to perform. It should also not involve many specialized tools so that other researchers or engineers can replicate the method. Thus, we explored a number of digital image processing techniques to see if we could determine glass bead density accurately and rapidly and which method met our two requirements.

The second research objective was to investigate the impact of bead density on paint pavement marking retroreflectivity. To do so we collected retroreflectivity data and glass bead images in the field. To achieve both research objectives we processed the digital images and performed a correlation analysis between the bead density and the marking retroreflectivity.

4.3 PAINTING MATERIALS AND PROCESS

This section introduces the reader to various aspects of glass beads and paint marking materials. We also briefly discuss the paint marking application process.

4.3.1 Glass Beads

The glass bead refractive index, diameter, roundness, their embedment depth, and their density in the paint all have impacts on the retroreflectivity values of the pavement marking as a whole. The amount of retroreflected light depends on these parameters and on the type of the glass beads. This paper focuses on depth and density.

A bead refractive index is dictated by the chemical and physical makeup of the glass material [VDOT 2008]. AASHTO standard M247-07 requires glass beads to have a refractive index of 1.50-1.55 [AASHTO 2007]. Glass beads are recognized to provide their best retroreflection when about 40% of each bead is exposed above the marking and 60% is embedded in the marking. The Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FP-03) specifies a glass bead application rate of 6 lb/gal or 12 lb/gal for waterborne paint depending on the type of glass bead used [FHWA 2003].

Five types of glass beads are defined in the FP-03. The classification of pavement marking glass beads into types is based on their gradation (size). The first two types of glass beads (I and II) are defined by an AASHTO standard and their gradations are shown in Table 4.1 [AASHTO 2007] as an example. The reader should recall that a smaller sieve size represents a larger hole and thus, a larger bead. Type I is referred to as a standard glass bead and type II is known as a uniform gradation glass bead [AASHTO 2007]. Types III, IV, and V glass beads are known as large beads. These are not shown here as they pass through a large group of sieve sizes (8-25). Readers should note from Table 4.1 that each type classification of bead is comprised of beads of various sizes as specified in the table at the percentage levels shown. The fact that a bead type does not contain same size beads has a profound impact on bead density.

Table 4.1. Gradations of Type I and Type II Glass Beads [AASHTO 2007]

Sieve Size	Sieve Size in µm[a]	Sieve Size in Inches	Mass Percent Passing	
			Type I	Type II
No. 16	1180	0.0469	100	-
No. 20	850	0.0331	95-100	-
No. 30	600	0.0234	75-95	100
No. 40	425	0.0165	-	90-100
No. 50	300	0.0117	15-35	50-75
No. 80	180	0.0070	-	0-5
No. 100	150	0.0059	0-5	-

Note: a 1000 µm= 1 mm

4.3.2 Paint Marking Material

Paint is mainly composed of finely ground pigments that are mixed into a resin or binder system. Various ingredients and additives are incorporated to obtain certain desired properties. A liquid (water or solvent) is added to the mixture to produce a material that is pliable by application equipment [VDOT 2008]. Water-based paint is more environment friendly than solvent borne paint. Water-based paint is currently the most commonly used pavement marking material.

Paint markings are typically 15 to 25 mils (0.015 to 0.025 inch) in thickness when applied. Paint drying time depends on the thickness and its composition as defined in the paragraph above. As a rule of thumb, a paint truck speed of 10-12 mph will result in a paint thickness of 15-18 wet mils without beads. Glass beads are usually dropped (using a mechanical pressurized means) into the wet paint as the paint is applied to roads [NCDOT 2006].

4.3.3 Paint Marking Application

Paint marking thicknesses and glass bead application rates are specified in the FP-03. However, thickness and application rate are very hard to control in the field during the paint marking application process. The quality of the markings generally depends on the experience of the paint crew.

Immediately after application, paint crew technicians examine the paint surface glass beads with a magnifier. If the glass beads are found to be too dense or too sparse (determined by a superintendent via visual inspection), the technicians will adjust the pressure in the glass bead tank or the glass bead dispenser until they obtain a satisfactory glass bead density. This paint truck calibration process is conducted on a test road to ensure that the applied markings have good qualities as determined by visual inspection. In the field, the paint crew normally cleans the bead guns and adjusts the bead tank pressure every morning before the paint application.

Paint crews also calibrate the bead guns using a kit form the bead manufacturers. The basic idea is that if we know how long it takes the truck to apply a gallon of paint, then hold a container under the bead guns and measure the volume of the beads after 10 seconds to get the number of pounds per gallon for glass beads. This can be used to compare with the specified values, 6 lb/gal or 12 lb/gal for waterborne paints, depending on the type of glass bead used [FHWAb 2003].

4.4 Methodology

The methodology used in this study was to collect field retroreflectivity values with a handheld retroreflectometer and photograph the marking surface using a digital camera. The digital images were analyzed and a bead density value was generated for each pavement marking line. Then, we analyzed the impact of bead density on paint pavement marking retroreflectivity.

4.4.1 Field Data Collection

We first describe the site selection and layout process. Then, we discuss how we collected marking retroreflectivity data and how we captured glass bead images in the field.

4.4.1.1 Site Selection and Layout

The paint data were collected on 40 secondary road sites in four highway divisions in NC. The sites were selected randomly on a set of two lane highways. The selected sites were deemed to be typical. These roads generally have low traffic volumes whose annual average daily traffic (AADT) is at or below 4000 vehicles per day. All measured roads were two-lane highways with asphalt pavement surfaces (chip sealed or plant mixed asphalt). The R_L measurements for each line were collected within a roadway section that was about 10 feet long. The date of marking installation was known for all sites. An example site layout is illustrated in Figure 4.1.

4.4.1.2 Retroreflectivity Measurement

The research team used a handheld LTL 2000 retroreflectometer for data collection. This retroreflectometer uses 30-meter geometry, which is the geometry required by ASTM Specification E 1710-05 [ASTMa 2005]. The standard operating procedure in the instrument manual was strictly followed during field data collection. Field calibration of the LTL 2000 was conducted at each site prior to the start of data collection.

Three measurements were collected for each white edge marking line in the direction of vehicle travel. For the yellow center lines, three measurements were collected in each direction because a previous study found that centerline retroreflectivity values measured in the direction of paint application are significantly higher than the values measured in the opposite direction [Rasdorf et. al. 2009]. Thus, six measurements for each yellow center line were collected. The average of the three measurements for white edge lines and the average of the six measurements for yellow center lines were used as the line retroreflectivity.

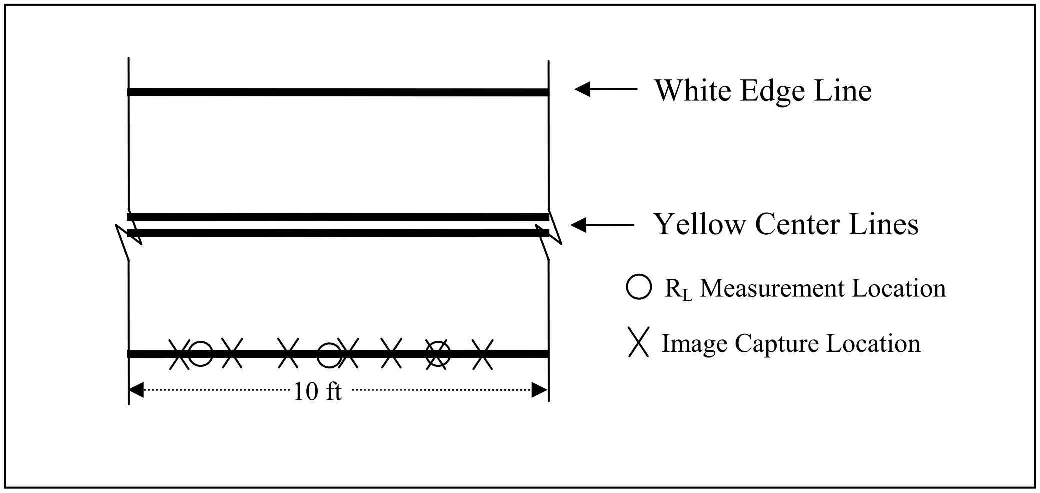


Figure 4.1. Field Data Collection Site Layout

Three measurements were collected for each white edge marking line in the direction of vehicle travel. For the yellow center lines, three measurements were collected in each direction because a previous study found that centerline retroreflectivity values measured in the direction of paint application are significantly higher than the values measured in the opposite direction [Rasdorf et. al. 2009]. Thus, six measurements for each yellow center line were collected. The average of the three measurements for white edge lines and the average of the six measurements for yellow center lines were used as the line retroreflectivity.

4.4.1.3 Image Acquisition

We photographed five to eight marking images with a digital camera in the same segment of the road as the R_L measurements were taken (Figure 4.1). The glass bead images were obtained using the macro zoom mode of a Canon SD camera. This camera enabled us to collect high-resolution images without a specialized digital image capturing device. Totally, about 1,000 glass bead images were collected over our entire study area of 40 sites. From these we selected 9 sites comprising 108 images. These sites were selected because they contained plant mixed asphalt surfaces rather than bituminous surface treatment pavements.

4.4.2 Bead Density Determination

Figure 4.2 shows an example of a good quality glass bead image (a 14 month old marking) collected in the field. One can clearly see that there are three primary elements on all images (as well as all of the other images): glass beads, paint background, and holes (voids) left by the glass beads when they are worn away.

Recall that both the Rich et. al. [2002] and Mizera et. al. [2009] studies were conducted on newly applied pavement markings. Such new markings do not typically have obvious glass bead loss. Few to no holes appear in them. Figure 4.3 shows an image of a newly applied pavement marking. Not a single bead is found to be worn away on the marking surface. Intuitively, we speculate that when time and traffic pass by, more glass beads are worn away and more holes are created (resulting in Figure 4.2, for example). The percentage of glass beads decreases while the percentage of holes increases with time. This is the primary cause of pavement marking retroreflectivity degradation over time − a reduction in bead density.

In the following sections, the manual, automated, and semi-automated methods used to determine glass bead density are presented.

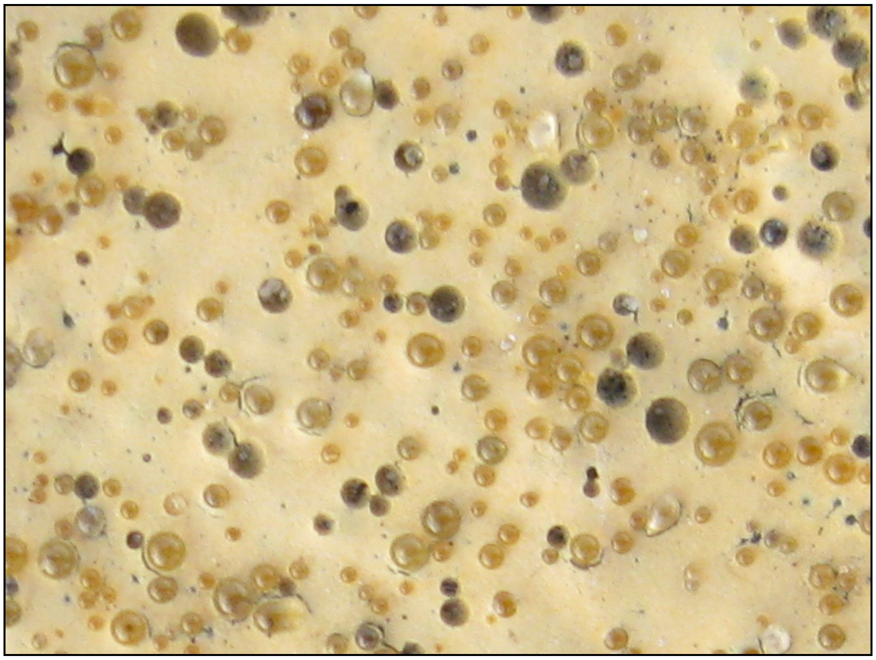


Figure 4.2. A Typical Glass Bead Image

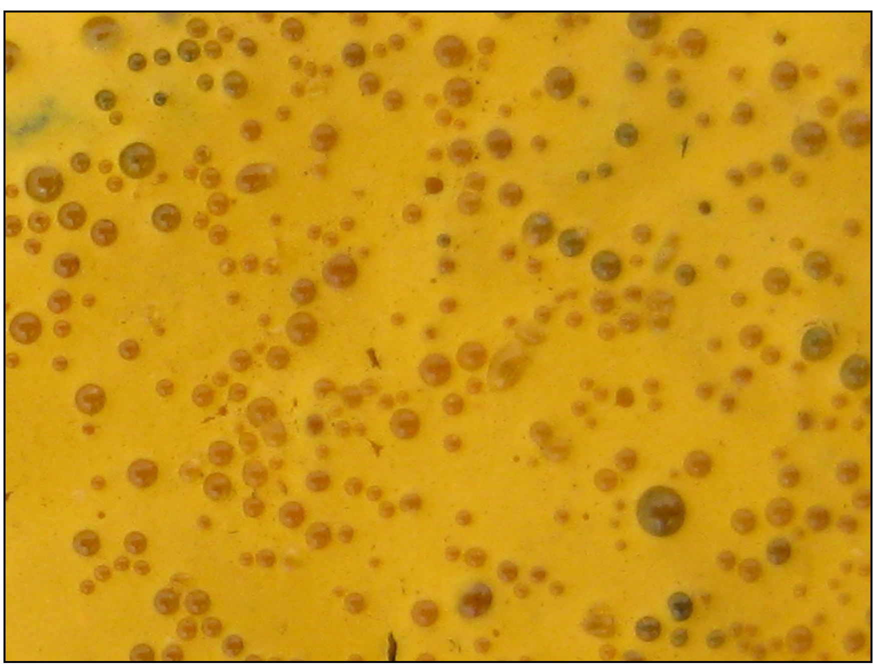


Figure 4.3. A Newly Applied Paint Pavement Marking Image

4.4.2.1 Counting − A Completely Manual Method

Mizera's manual counting method provides one way to calculate glass bead density. Using images of a predefined area (such as 2 inches by 2 inches) on the marking surface one can count the number of the beads in the area. If the average bead size (diameter) is known, the total surface area of all glass beads can be estimated. Then, the total area of glass beads is divided by the total marking area to determine the bead density.

We assume that the pavement markings in our study contained standard Type I glass beads (The graduation of glass beads used in NC is actually different from AASHTO Type I beads). From Table 4.1, we can determine that the median diameter of a Type I glass bead is same as the size of a No. 40 Sieve, which is 425 μm or 0.0165 inch. Thus, the median area of a Type I glass bead is 0.214×10^{-3} inch^2. The mean diameter is estimated to be 455 μm using the gradation of Type I glass beads.

Thus, it is possible to manually determine the bead density of an image (using the above procedure and the estimated median area of a Type I glass bead) by counting the number of visible beads. However, the estimated bead density values using this approach are not accurate. The reason for this is evident by a close inspection of Figure 4.4 which illustrates three typical cases of glass bead embedment. When more than half of a glass bead is embedded in the paint binding material it is most secure and is least subject to being dislodged. The second and third types of embedment (half of the glass bead, and less than half of the glass bead) result in beads that are much more easily worn off, especially when the markings are exposed to traffic for longer periods of time. Most glass beads that remain in older markings are embedded more than half way. Thus, most images (and most pavement markings) contain more deeply embedded beads only. Clearly, the surface area of a bead embedded this way is actually smaller than the estimated median area outlined in the procedure above because the true area is established by the chord length C rather than by the bead diameter D (Figure 4.4). Thus, C < D and the area of type 1 embedment is smaller than the area of types 2 and 3. Thus, the estimated bead densities from the counting method are higher than the actual values. It should be noted that one could convert an estimation of diameter D to chord length C by employing an assumption of the average percentage of a bead that is embedded. However, the assumption may be erroneous. Without an assumption of the average percentage of the bead that is embedded, the manual counting method can accurately produce a glass bead count (and perhaps an initial density) but not an accurate glass bead density for older pavement markings.

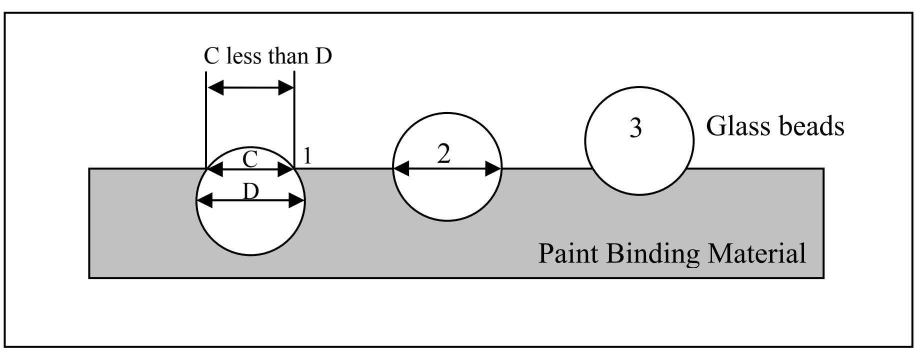


Figure 4.4. Glass Bead Embedment Scenarios

4.4.2.2 Automated Image Processing

The ideal solution for determining glass bead density is to find an image segmentation algorithm and use a computer to automatically process the glass bead images. To explore this approach we studied several image segmentation methods including global thresholding, region growth, and marker-controlled watershed segmentation. Unfortunately, we found that none of these methods works reliably and none can produce an accurate estimation of the bead density. We discuss those methods in the following sections.

Global Thresholding

Thresholding is based on the grayscale histogram of an image. The histogram shows, for each gray level, the number of pixels in the image that have that gray level. Figure 4.5 shows the grayscale histogram of Figure 4.2. The x-axis quantifies the gray scale levels which represent pixel intensity. Pixel intensity has 256 levels where level 0 represents black and level 256 represents white. The y-axis represents the number of pixels or the frequency of occurrence of a pixel intensity level. Thus, Figure 4.5 shows that (in Figure 4.2) there are about 2,500 pixels of intensity level 150 and about 15,000 pixels of intensity level 210.

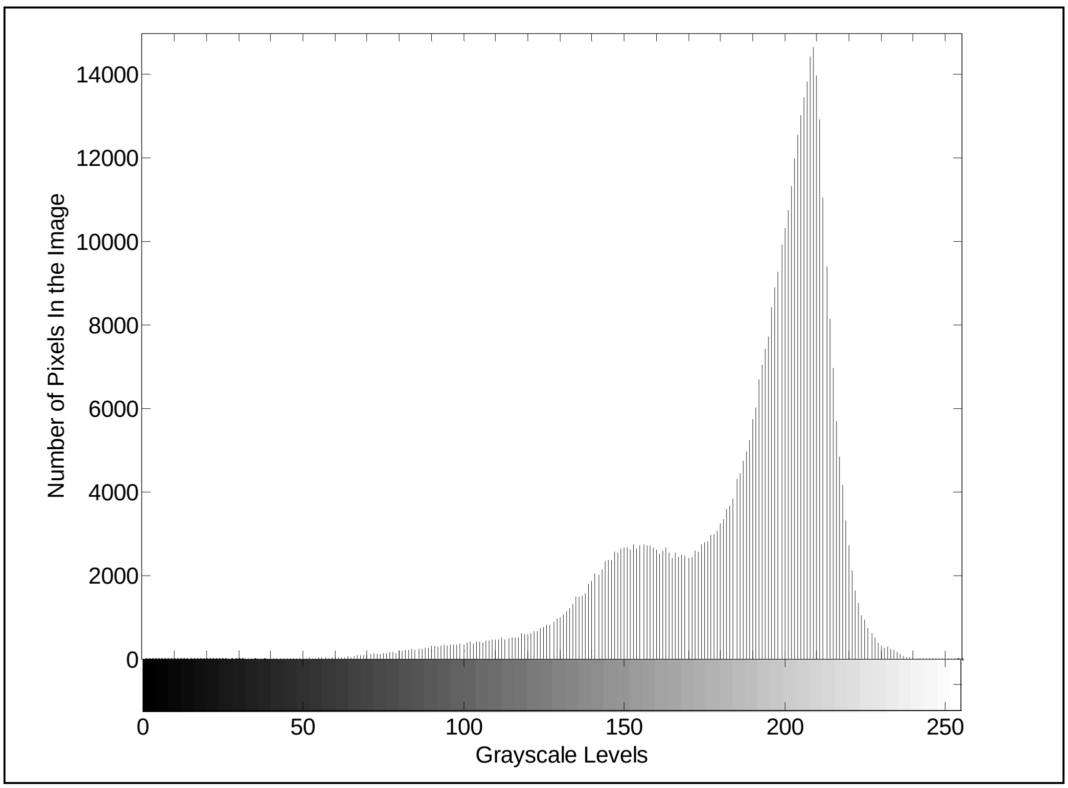


Figure 4.5. Histogram of the Grayscale Image of Figure 4.2

An analysis of the Figure 4.2 image reveals that there are three primarily elements of interest − beads, voids, and background. In Figure 4.5 it is seen that the element with gray level range of approximately 60-120 represents darkness (holes) in the image. The element with a gray level range of approximately 120-170 represents the glass beads. The element with a gray level greater than 170 represents very light grayscale − the background paint. The threshold which separates the holes from the glass beads is somewhere between 110 and 130. The threshold which separate the glass beads from background paint is somewhere between 160 and 180. But where exactly and how can this be determined? There is no clear answer.

Still, if the thresholds were able to be determined this way one could then calculate the hole density and bead density by analyzing the binary images in an automated fashion. The number of pixels in any of the three critical areas divided by the total number of pixels would yield the required density.

However, the global thresholding method has serious drawbacks. First, the bead and hole density values are too sensitive to the thresholds. For example, if we select 120 as the threshold separating holes and beads for the image with the histogram shown in Figure 4.5, a selection of 165, 170, or 175 as the threshold separating beads and backgrounds would result bead density values of 17.4, 20.0, and 22.7%. Thus, a change in threshold value from 165 to 175 results in as much as a 5 to 6% difference in bead density.

Finally, Figure 4.5 represents one of the best histograms we obtained. Figure 4.6 illustrates another valid histogram of our images. The reader can clearly see that discernable break points between beads, voids, and background are not in evidence. Thus, after having processed hundreds of images using this approach we did not find it to be fruitful.

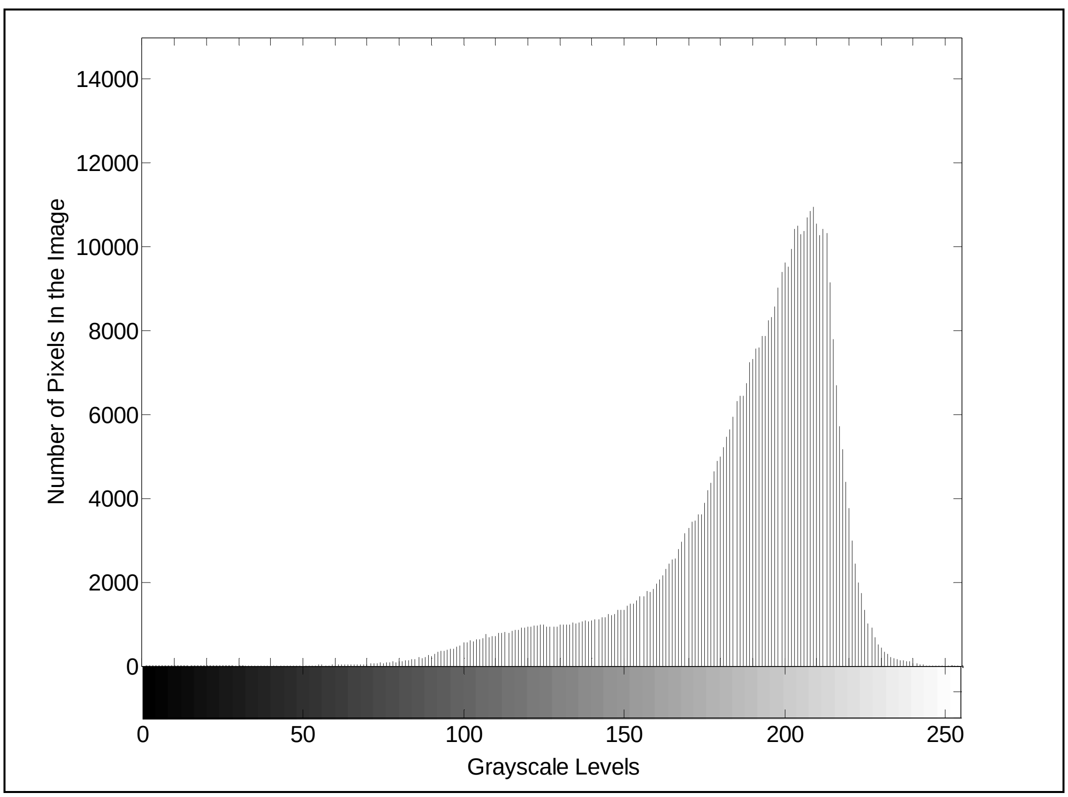


Figure 4.6. Randomly Selected Histogram

Region Growth

Region growing is a procedure that groups pixels or sub-regions into larger regions based on predefined criteria. The basic approach is to start with a set of “seed” points and from these grow regions by appending to each seed those neighboring pixels that have properties similar to the seed [Gonzalez and Woods, 2003]. For the images with histograms similar to Figure 4.5, the starting points were set to be the pixels with grayscale levels less than a threshold (such as 100 for Figure 4.5).

The difficulty of the region growth method is twofold − first, what is the threshold and second, what is the formulation of a stopping rule? Both of these problems have to do with finding the cutoff points (boundaries or thresholds) between the beads, voids, and background and neither method enables us to do so satisfactorily.

Marker Controlled Watershed Segmentation

The watershed segmentation method has been used to find drainage basins and watershed ridge lines in an image by treating the image as a surface where light pixels are at high elevations and dark pixels are at low elevations. Watershed segmentation often produces more stable segmentation results than other methods. The concept of watershed segmentation and its algorithms are described in detail by Gonzalez and Woods (2003). Our findings are that directly applying the watershed segmentation method to a glass bead image leads to over-segmentation, which means the image is segmented into too many regions. We did consider an approach used to control segmentation that is based on the concept of a marker [Gonzalez and Woods 2003]. We applied the marker controlled watershed segmentation to our bead images. The glass bead density values produced by the watershed segmentation method were either unreasonably high or low. The method was not considered to be accurate or reliable.

4.4.2.3 Computer-Aided Counting − A Semi-automated Method

All of the manual counting and automated image processing methods we investigated or considered failed to satisfactorily generate the desired bead density values for a large range of images. Thus, we considered combining the two methods and created an approach we refer to as computer-aided counting.

Glass beads are generally round in shape. Thus, we can determine the center and the radius of a glass bead by knowing the coordinates of three points in its circumference. If two of the three known points and the center point of the circle are in a line, the center and the radius of the glass bead (circle) can be determined by using only the two points on the circumference.

We developed a bead density analysis program (BDAP) to take this into account. The program requires two mouse clicks to select a glass bead on an image. The positions of the two clicks must be at the two end points of a diameter. If the coordinates of the two mouse clicks are (x1, y1) and (x2, y2), the center of the glass bead then is ((x1+x2)/2, (y1+y2)/2) and the diameter of the glass bead is D=$\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$. If the entire glass bead is contained within the image (as is Bead 1 in Figure 4.7) the area of the bead is

$$A = \pi \times (D/2)^2$$

If a small portion of the glass bead is outside of the image (such as Bead 2 in Figure 4.7), the area of the bead is

$$A = \pi \times (D/2)^2 - \alpha (D/2)^2 + d(D/2)\sin\alpha$$

Where,

d = Distance from the center of the bead to the edge of the image

α = The angle $\arccos(2d/D)$ in radius

If more than half of a glass bead is outside of the image (such as Bead 3 in Figure 4.7), the program user needs to imagine the point outside the image (point 2 of Bead 3 in Figure 4.7). Then, the area of the bead is calculated as:

$$A = \alpha (D/2)^2 - d(D/2)\sin\alpha$$

Where the D and α have the same meaning as in the previous equation.

The overall area of an image is calculated by multiplying the image width and image height. The area of the beads is the sum of the areas of each glass bead. The bead density is then obtained by dividing the total bead area by the overall area of the image.

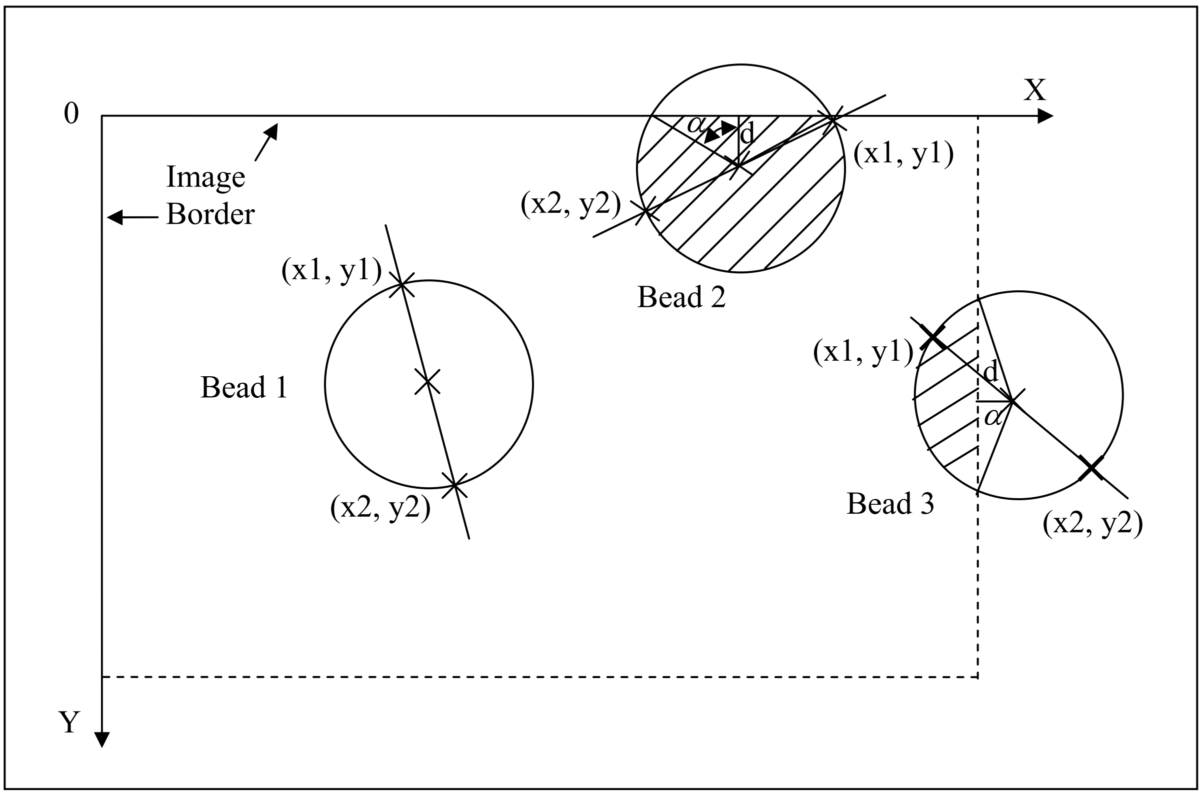


Figure 4.7. Glass Bead Area Calculation

The flowchart of the computer aided counting method algorithm is shown in Figure 4.8. The first steps include loading the image, calculating the image size, and enlarging the image according to a user input ratio that supports good visualization. The user can then select a bead with two mouse clicks. The program calculates the bead area and updates variables representing the total area of beads (BeadArea) and the number of beads counted (BeadNum). The beads are selected one by one until they have all been measured. The program outputs the cumulative bead density and the number of beads contained within the image. The program could also be used to determine hole density and the number of the holes in the image.

Figure 4.9 illustrates the bead selection process described by the algorithm. When a bead is selected (two mouse clicks), the program graphically circles and numbers the bead. Figure 4.9 shows that 15 beads have been selected so far. The total area of selected glass beads is 7,208 image pixels. The total area of the image is 480,000 (800 × 600) pixels. The calculated bead density for these 15 beads is 1.9%. The selecting process should continue until the last bead is selected and all beads are cumulatively tallied.

The computer-aided counting method works well on the field collected images. Because it is (regrettably) only a partially automated method, about 10 minutes are needed to analyze each image. While not ideal this is not unreasonable given the value of the results that can be obtained.

4.5 Results

It is important to note that the quality of the images collected from plant mixed asphalt pavement is much better than the images from chip sealed pavement. Images from 9 sites (with markings applied on plant mixed asphalt pavement) were processed. Each site has four marking lines. We processed three images for each line resulting in a total of 108 images processed.

The three bead density values for each pavement marking line were averaged to determine the bead density for the marking line. Doing so accounted for keep variations in point density values. Table 4.2 shows the bead density and retroreflectivity values at one measurement location (Site 11). The values in the column titled "Line Density" and the column titled "Line R_L" are used in the correlation analysis.

Table 4.2. Bead Density and Retroreflectivity Values at Site 11

Image Name	Color	Bead Density in Percentage		R_L in mcd/m^2/lux		
		Point Density	Line Density	Point R_L		Line R_L
No11-SR1613-03.JPG	White	16.9	18.6	294		311
No11-SR1613-04.JPG	White	19.6		306		
No11-SR1613-06.JPG	White	19.3		333		
No11-SR1613-10.JPG	Yellow	14.3	14.7	122	97	118
No11-SR1613-11.JPG	Yellow	15.6		132	102	
No11-SR1613-12.JPG	Yellow	14.3		149	107	
No11-SR1613-19.JPG	Yellow	14.2	13.5	122	98	110
No11-SR1613-20.JPG	Yellow	13.9		134	85	
No11-SR1613-21.JPG	Yellow	12.4		126	96	
No11-SR1613-28.JPG	White	14.9	14.7	260		273
No11-SR1613-29.JPG	White	14.7		265		
No11-SR1613-30.JPG	White	14.5		295		

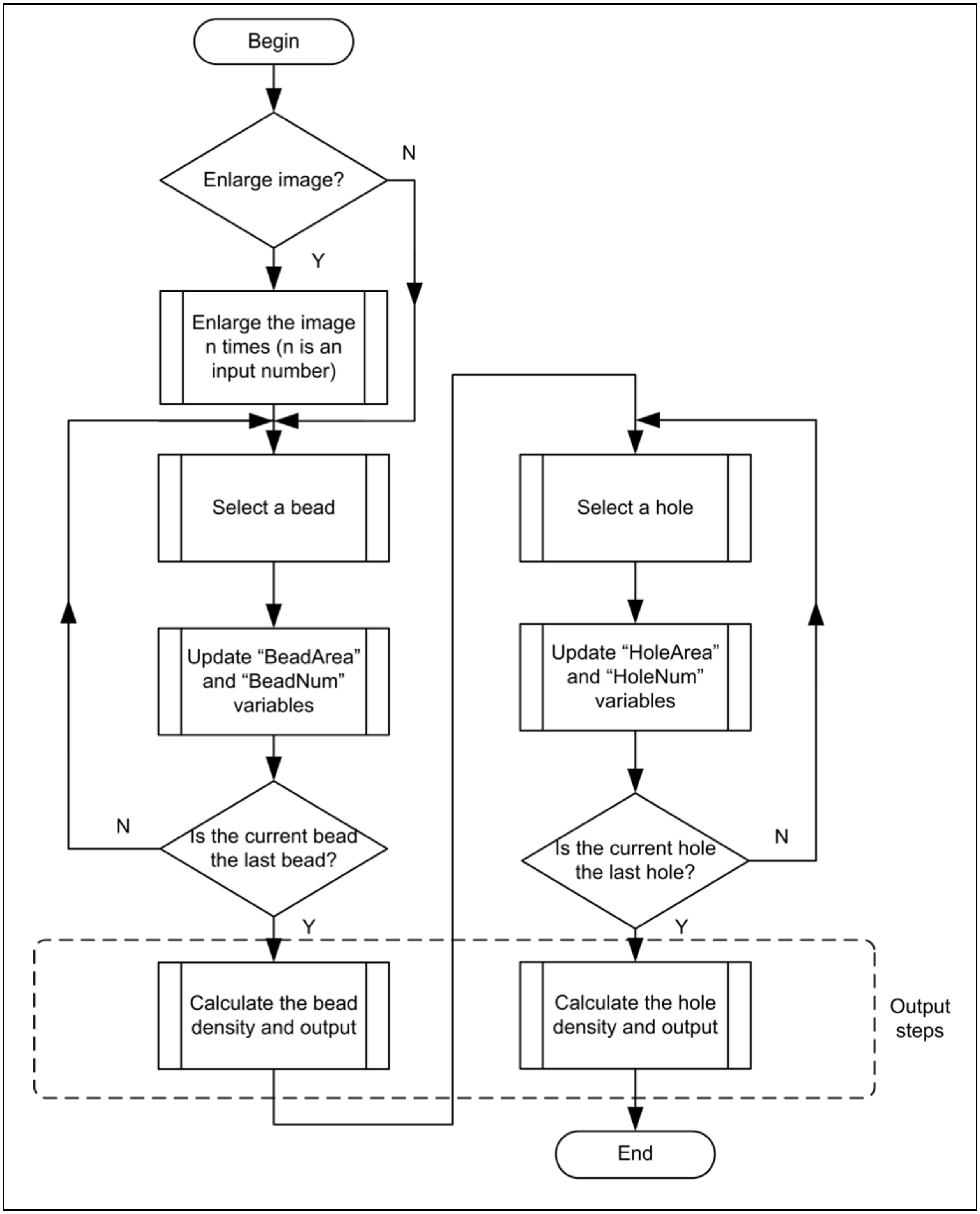


Figure 4.8. Computer Aided Counting Method Algorithm

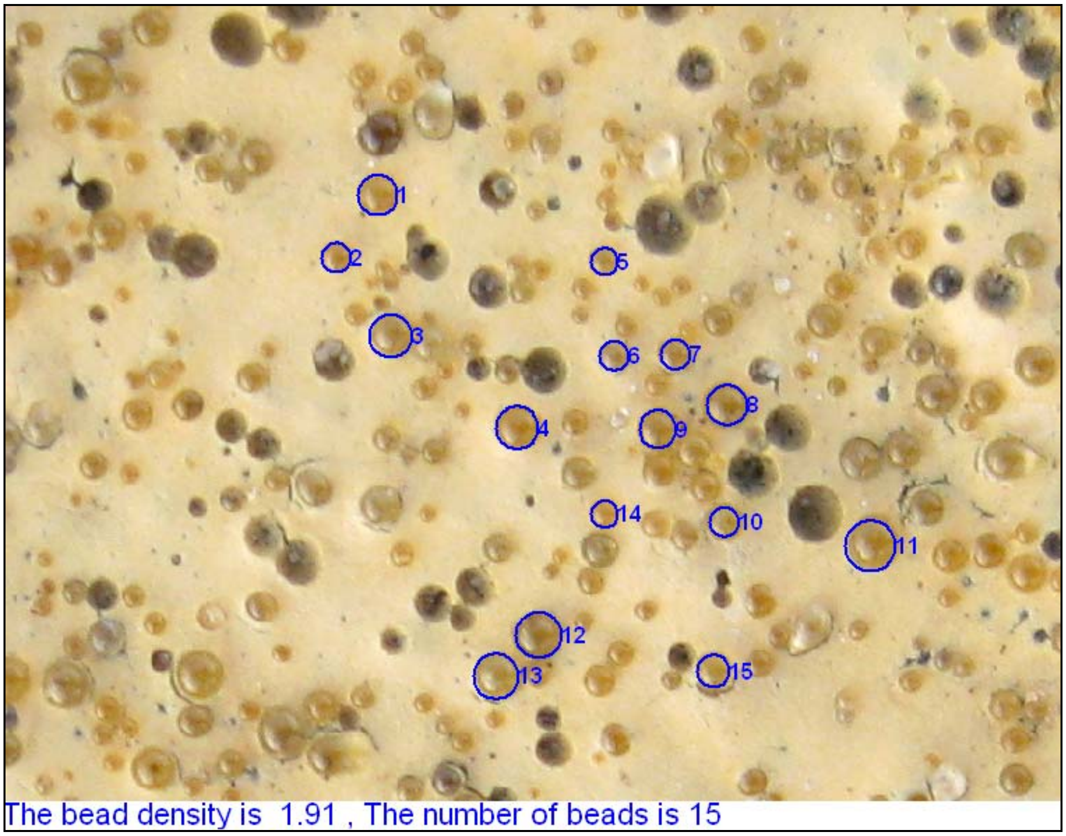
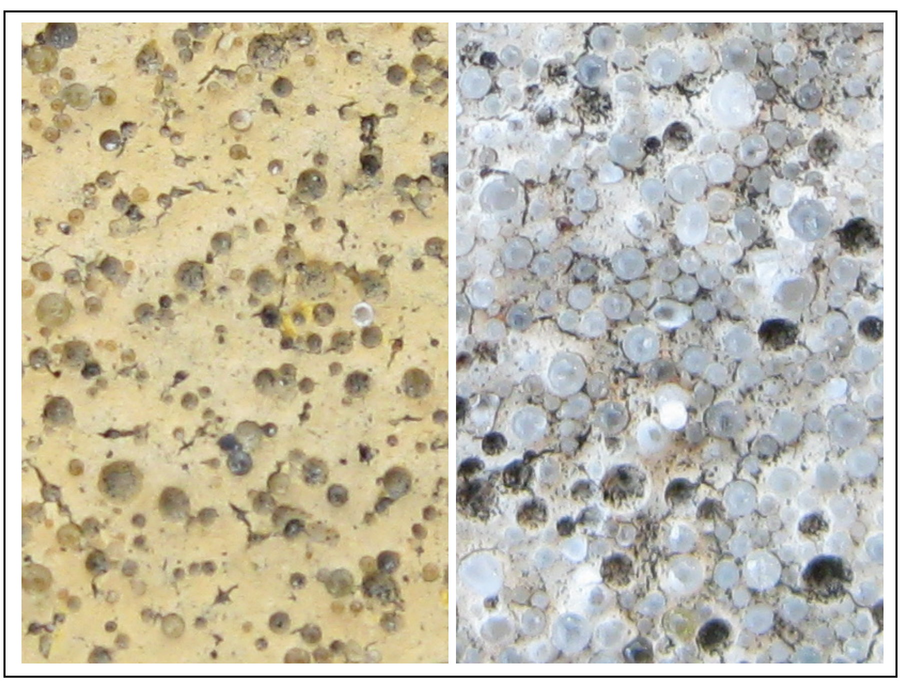


Figure 4.9. Computer Aided Counting Process



(a) (b)

Figure 4.10. Marking Images with Very Low and Very High Bead Densities

Three white edge markings had bead density values of 26.1%, 27.9%, and 30.7%. The glass beads on those roads are especially dense. Figure 4.10 (b) shows one of the images from the marking lines with a bead density of 30.7%.

The 9-24% bead density range is comparable to Rich's research results [Rich et. al. 2002]. Rich's study measured three paint sample sites and the approximate bead densities of these paint markings were 8, 18, and 20%. The 18% and 20% bead densities are in the range of 9-24%. A bead density of 8% is very close to this range.

Figure 4.11 clearly shows that bead density values have a positive correlation with the marking retroreflectivity readings. The linear regression equations for the white edge markings and yellow center markings are:

R_L (white) = 90.0 + 9.50 × Density (R^2 = 0.73)
R_L (yellow) = 52.7 + 6.11 × Density (R^2 = 0.61)

Where:

R_L = Retroreflectivity of pavement markings in mcd/m^2/lux
Density = Bead density in percentage

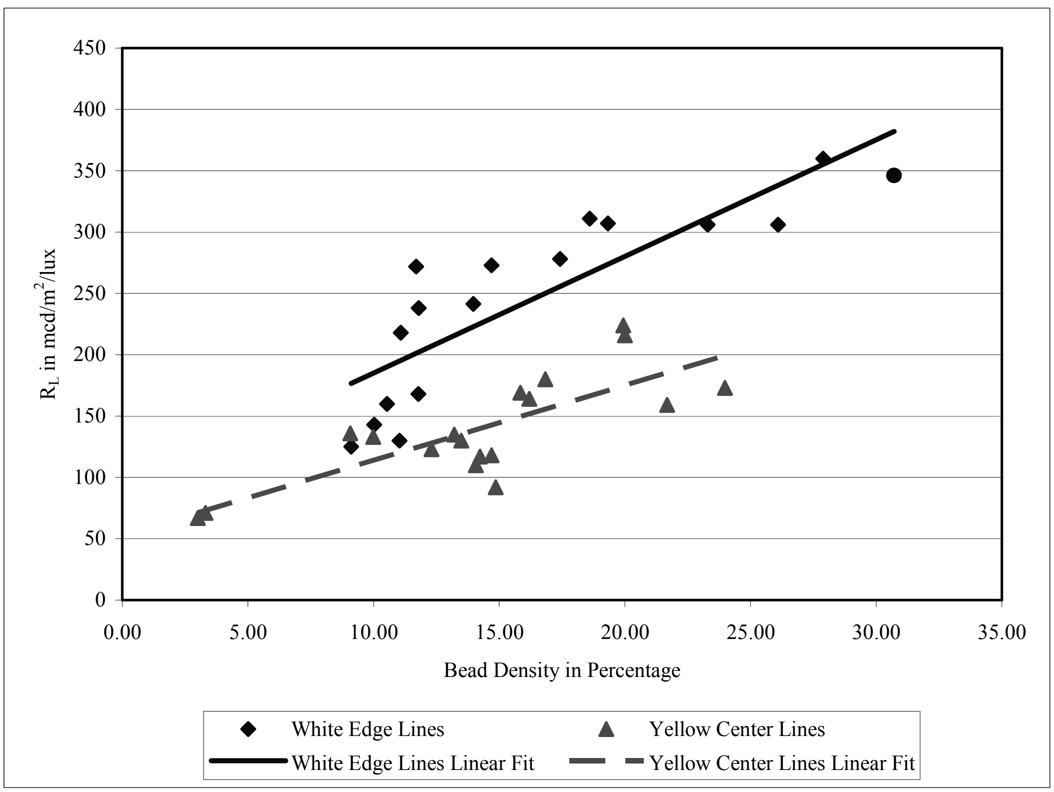


Figure 4.11. Bead Density and Retroreflectivity Relationship

The values of 9.50 and 6.11 are the slopes of the regression lines. The positive signs of the two values indicate that retroreflectivity readings increase as bead density increases. The coefficient of determination, R^2, is the proportion of the variability in the response explained by the regression model, which can be used to determine how well the regression line approximates the real data. The R^2 values of 0.73 and 0.61 for white edge lines and yellow center lines indicate the regression lines fit the data reasonable well. We also fitted the data using a quadratic curve and found the result was slightly better. Give the small sample size of the study (18 points for each type of markings), a linear regression fit is considered to be satisfactory.

Notice also that the regression line for white edge markings is significantly higher than the regression line for yellow center markings. Thus, white edge markings have higher retroreflectivity values than yellow markings when the bead density values are same. For example, when the bead density is 15%, white markings have a retroreflectivity value of 233 mcd/m^2/lux while yellow markings have retroreflectivity value of 144 mcd/m^2/lux. This is approximately 60% more R_L for white lines. This research result is consistent with the findings of a previous study by Craig et. al [2007] showing that white edge lines generally have higher retroreflectivity values than yellow center lines.

Table 4.3 summarizes the relationship between bead density and retroreflectivity. If a bead density value is in the range of 9-15%, white edge lines and yellow centerline markings have retroreflectivity values between 175-232 mcd/m^2/lux and 107-144 mcd/m^2/lux, respectively.

Table 4.3. Bead Densities and Retroreflectivity Values

Bead Density in Percent	White Edge Line R_L	Yellow Center Line R_L
<9	<175	<107
9-15	175-232	107-144
15-20	232-280	144-174
20-25	280-327	174-205
>25	>327	>205

The FHWA and other transportation agencies are working together to establish a minimum retroreflectivity standard for pavement markings. A recent FHWA publication proposed recommendations for the minimum levels of pavement marking retroreflectivity which were based on the results of a Target Visibility Predictor (TARVIP) computer model [FHWAc 2007]. If the paint truck speed is in the ranges of less than 50 mi/hr, 50-70 mi/hr, or greater than 70 mi/hr, the recommended minimums are 40, 60, or 90 mcd/m^2/lux for fully marked roadways (with edge lines) where retroreflected raised pavement markers (RRPMs) are not provided. Our study shows that for pavement markings with a 10% bead density, white edge lines and yellow center lines have predicted retroreflectivity values of 185 mcd/m^2/lux and 114 mcd/m^2/lux respectively. Generally speaking, this is more than enough retroreflectivity for drivers and it is well above the recommended minimum.

4.6 Conclusions

The image processing techniques we studied did not satisfactory enable us to determine bead density. The bead density results from the complete manual counting method tend to be higher than the actual values. None of the three automated methods (global thresholding, region growth, and marker control watershed segmentation) yielded reliable and satisfactory bead densities for the field collected images.

However, we did find a semi-automated compromise that can satisfactorily be used to obtain bead density values from paint pavement marking images. The method is easy to use and has a relatively low cost. Most importantly, it is quite accurate. The bead density values obtained from multiple tests of the same image are normally very close to each other (typically within a range of ±1%). The method can also be applied to other types of markings.

Our findings clearly indicate that glass bead density has a significant impact on marking retroreflectivity. Higher glass bead density leads to higher marking retroreflectivity. Furthermore, white edge markings have conclusively higher retroreflectivity values than do yellow center markings when the bead density values are the same.

The bead density values in the tested NC pavement markings are most normally in the range of 9-24 percent of the paint marking surface. Markings with bead density values lower than 9% are considered to have too few glass beads on the marking surface to provide acceptable retroreflectivity. This knowledge could be used by state DOTs to select a suitable and desirable bead density and then monitor the glass bead application process to ensure the achievement of the desired density.

4.7 Recommendations

It is recommended that a similar study be conducted for other types of pavement markings, especially thermoplastics. This study focused on paints because they comprise the majority of markings. Additionally, the traffic control required for data collection was much easier on two-lane highways than on other types of highways. Other types of pavement markings are expected to have a similar correlation between retroreflectivity and bead density values, but the regression lines are expected to have different intercepts and slopes.

A similar study on different types of pavement surface materials (such as chip sealed asphalt surface, concrete pavement) is also recommended. A study should also be conducted in different climate zones, especially in a northern area where weather and temperature are more severe than in NC.

This study was conducted on two-lane highways with low traffic volumes. A similar study could be initiated to evaluate bead density differences on high traffic volume roads. We also recommend conducting a similar study using larger glass beads. Such a study could evaluate whether markings with large glass beads provide better retroreflectivity than markings with standard glass beads if the bead densities are same.

The retroreflectivity values have an obvious variation when the bead density is in the range of 10-15 percent as indicated in Figure 4.11 especially for white edge lines. The colors of the markings are observed to vary for both white edge and yellow center markings. The marking color (within white or within yellow) is speculated to be another factor with a significant impact on marking retroreflectivity. Thus, we recommend conducting a chromatography study to determine whether or not marking color plays a role in determining marking retroreflectivity.

Finally, it would be interesting to study how the bead density values change over time. Our images showed that some old markings have a high hole density. It would be possible to determine when the holes are formed (the glass beads are worn away) if we know the marking bead density values over time. By conducting such a study, we could know more about the physical process of pavement marking retroreflectivity degradation over time. Thus, we could determine an optimal initial bead density range for new paint striping in order to achieve good R_L performance for the whole life cycle of paint markings.

5.0 THE IMPACT OF REGION ON PAVEMENT MARKING PERFORMANCE

Climate factors are intuitively thought to have impacts on the pavement marking performance. The same pavement marking materials are believed by many engineers to perform differently when installed in a northern state or a southern state. The snowplow has long been recognized to have significant impacts on pavement marking retroreflectivity deterioration. An early study conducted in Michigan found that the snowfall is correlated to the retroreflectivity degradation rate, assuming the snowplow frequency is proportional to the snowfall amount [Lee et. al. 1999]. The study concluded that the winter maintenance activities, such as snowplowing and using ice control materials, are likely to have a greater impact on the rate of decay than traffic volume, speed limit, and commercial traffic. Most northern states consider snow removal conditions and the methods used to remove snow or ice when selecting pavement marking materials.

However, there are numerous difficulties with modeling snowplow effects on pavement marking retroreflectivity degradation rates. First, there are no accurate records of the number of times that a road is plowed. Second, there is no indication of whether the snowplow blade actually hits or crosses the pavement markings. In order to know the snowplow effects, a controlled study, where an observer is present at the site, needs to be conducted to obtain valid data relative to snowplow effects. In addition, climate factors like precipitation and temperature may also have an impact on pavement marking performance. The effects of the individual climate factors on the pavement marking performance are difficult to obtain.

North Carolina is about 560 miles long from east to west. The state can be divided into three distinct topological regional areas in the east-west orientation. The mountain area is in the west and the elevation in most of mountain areas is more than 1200 feet. The coast area is in the east and the elevation of the coastal area is less than 300 feet. The central area is in the middle and the elevation of the central area is in the range of 300-1200 feet. There are also climate differences among the three regions as Section 5.1 details. The temperature in the coast area is higher than the mountain area. The precipitation amount in the coast and mountain areas is higher than that in the middle area. The snowfall amount is highest in the mountain area.

Previous research by others focused on the impact of pavement marking retroreflectivity on a driver's visibility and how pavement markings degrade over time. There is a gap in the current knowledge of how the regional or climate factor affects the rate of degradation. This study compiled white thermoplastic retroreflectivity data collected in North Carolina into three regions and compares their degradation rates in their first three years of their service lives.

5.1 Climate Regions

This section describes climate differences among the regions of NC. North Carolina can be divided into three climate regions. Historical temperature, precipitation, and snowfall data were obtained to show the climatic difference in the three areas. Figure 5.1 shows the temperature thematic map. The temperature decreases from the east to the west where the surface elevation is increasing. Figure 5.2 shows the annual mean total precipitation. The coast area and mountain area have more rain than the middle area. The temperature and precipitation data were acquired from the United State Department of Agriculture (USDA). The data used to compute the average values were collected during 1971-2000. NCDOT divides the whole state into 14 divisions. The division boundaries and the division numbers are also shown on the maps. When we divide the state into climatic regions, we will use the NCDOT division as the smallest unit.

Figure 5.3 shows the thematic map of annual mean total snowfall in North Carolina. The snowfall data were obtained from the National Climatic Data Center's (NCDC) climate maps of the United States. The original data were measured to a tenth of an inch and were collected during the period of 1961-1990. The mean annual value was computed by taking the 30-year mean of the yearly means. Although the climate is constantly changing, a 30-year period is long enough to illustrate the differences in the three areas.

Considering the patterns on the temperature, precipitation, and snowfall thematic maps, we could divide North Carolina into three regions by division. The coast region includes divisions 1, 2, and 3. The mountain area includes divisions 11, 13, 14. Divisions 4 and 12 are considered as transition areas. These areas are not actually coastal or mountain areas, yet they are not typically treated as central areas by the NCDOT. The retroreflectivity data from these two divisions are not used in the comparison. All other divisions are considered to be in the central area. Figure 5.4 shows the climate regions of North Carolina. The summary climate statistics of the annual average temperature, the annual mean total precipitation, and the annual snowfall range in the three regions are shown in Table 5.1.

5.2 Retroreflectivity Data Analysis

This section describes how the retroreflectivity data were collected and the volume and geographic distribution of the collected data samples in each area. The section also describes the data analysis.

5.2.1 Retroreflectivity Data Collection and Organization

The data used for this analysis were collected by the Laserlux vehicle-mounted mobile collection device which was calibrated with an LTL 2000 handheld device. Using a contractor (Precision Scan) NCDOT decided to collect retroreflectivity data via a mobile device because of the ability to collect a large amount of data in a safe and efficient manner. This data collection took place from June 1999 through June 2007 and resulted in a database of nearly 30,000 lane miles of data throughout NC The use of a contractor enables NCDOT to use state of the art equipment and experienced personnel without having to purchase equipment or permanently hire qualified personnel. NCDOT also felt that eliminating the need for a technician to choose a specific measurement spot (as is done with a handheld device) ensured that the collection remained objective.

The retroreflectivity data are organized into records for road segments. A road segment is defined as a portion of a road of varying length on which the pavement material, pavement marking system, and marking color are uniform and continuous. Segments measured in this study vary in length from 0.2 to 32 miles. The retroreflectometer took continuous readings while the vehicle was in motion and filtered out any invalid readings. All valid readings were averaged for every tenth of a mile and the average value recorded in the database. An overall average was then computed for each road segment. Segments were measured initially within 30 days of application of the pavement marking, then again after 6 months, and finally 1 year after application. Further readings were taken annually for 5 years so that there could be seven data points between the initial observation and the 5-year mark. Because of the ongoing nature of the data collection, only some of the road segments had a full compliment of data and most roads had been under observation for some period less than 5 years.

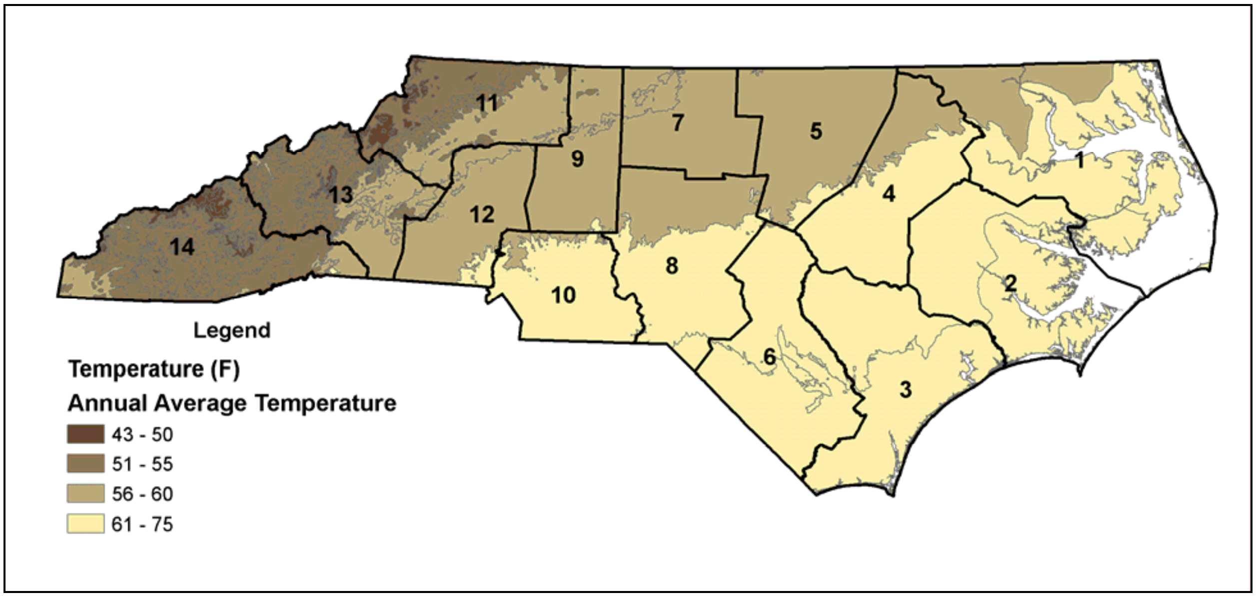


Figure 5.1. Annual Average Temperature [USDOA, 2008]

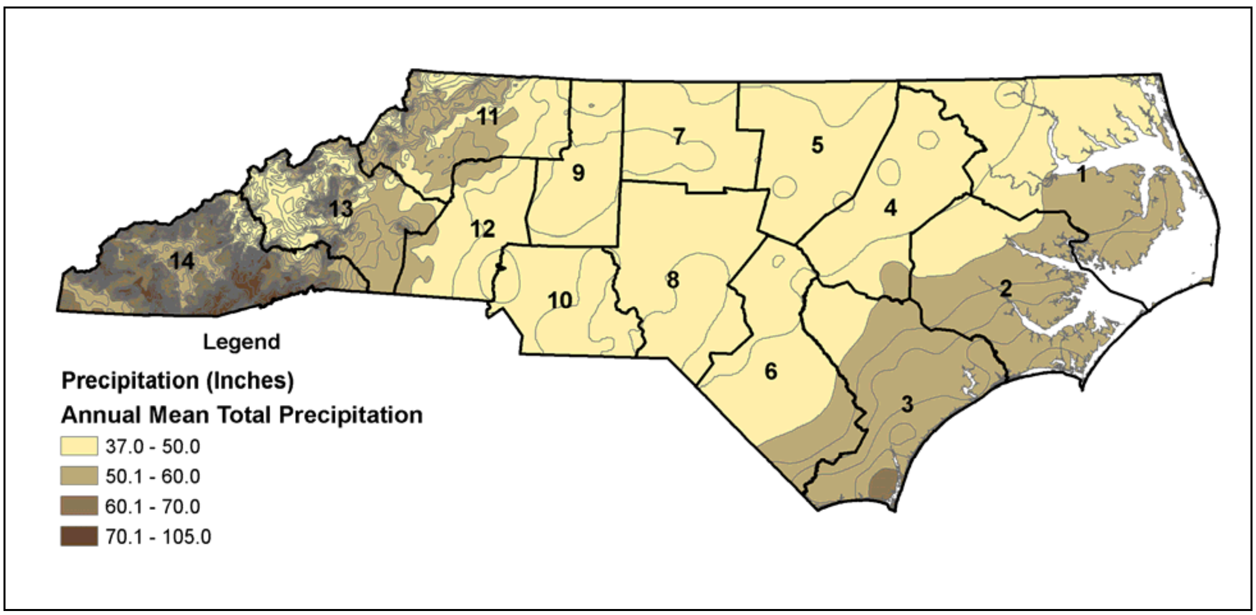


Figure 5.2. Annual Mean Total Precipitation [USDOA, 2008]

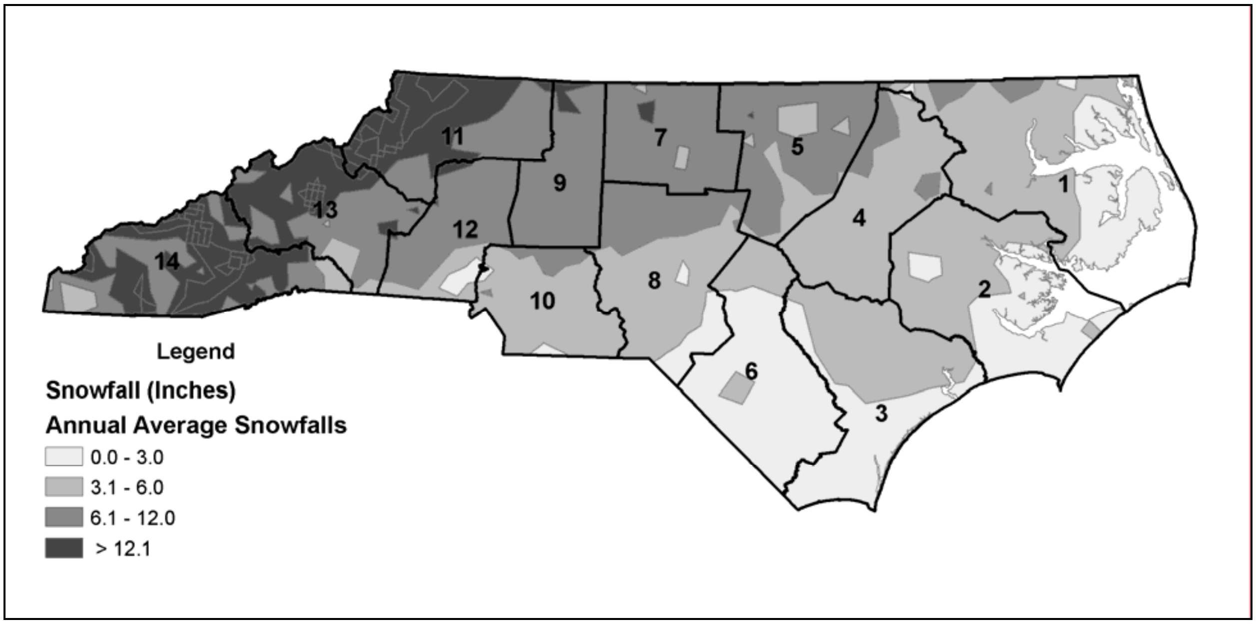


Figure 5.3. Annual Mean Total Snowfall [NCDC, 2008]

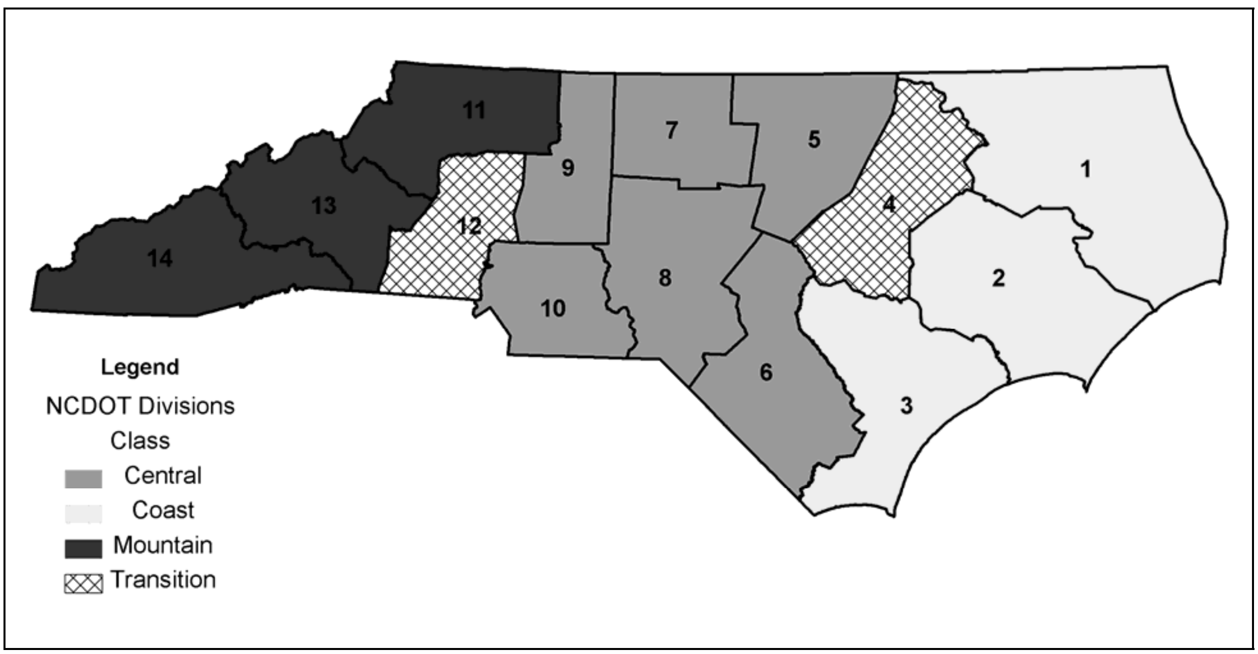


Figure 5.4. North Carolina Climate Regions

Table 5.1. Summary Climate Statistics in the Three Regions

Annual Statistics	Coast	Central	Mountain
Mean Temperature (ºF)	62.0	59.6	52.4
Mean Precipitation (Inches)	55.0	49.0	65.5
Snowfall Range (Inches)	0-6.0	3.0-12.0	6.0-20.0

For the purpose of this report, the data were reorganized into three regional categories. A previous study by the research team revealed that the lateral location of pavement markings has a significant impact on the degradation rates. There is significant evidence which shows a difference in the rate of retroreflectivity degradation between edge lines and center lines for both yellow and white thermoplastic markings. The results indicate that edge lines degrade at a slower rate than center or skip lines for both white and yellow thermoplastics. The lateral location study adopted an ANOVA analysis approach. In this study, we considered the lateral location and marking color as categorical variables and used both ANOVA and longitudinal data analysis methods to analyze the degradation rates based on region.

5.2.2 Data Distribution and Quantity

The collected retroreflectivity data were not evenly distributed in the three regions. Most data were collected in the central area. The number of white thermoplastic observations is largest in the database so these data were being used to analyze the regional effects. As noted before, lateral location and marking color were treated as categorical variables. Lateral line locations were categorized as either center or edge lines. Center lines were skip lines on a 4-lane highway in this study. Due to the limitation of the data, comparisons were only made using center and edge lines of white thermoplastic markings in different regions. Other types of markings do not have enough data to conduct the comparison.

Tables 5.2 and 5.3 list the mean retroreflectivity values, standard deviations, and sample sizes of white edge and white skip thermoplastic readings in the three regions. The data were measured over a five-year period. As reported in the December, 2007 quarterly report, the retroreflectivity values generally increase in the fourth and fifth year. This is shown in Tables 5.2 and 5.3 by the shaded cells. One explanation for the increases is that some road segments with low retroreflectivity values were removed from measuring during the period. The mobile retroreflectometer may not be able to take measurements when retroreflectivity is low (below 60 mcd/ m^2/ lux). Thus, such data are not included in the data set and the remaining values are then biased and higher. For this regional study, to eliminate these effects we have considered the first three years of measurements and compared their retroreflectivity values.

Figures 5.5 and 5.6 display the white edge and white skip retroreflectivity readings. From these two figures, we observed that the retroreflectivity values are lower in the mountain area than in the central and coastal areas. For the white edge thermoplastic in the mountains, the R_L value was in the middle at the initial time and was lowest after 36 months. The values at the 6-month and 12-month periods were the lowest for the mountains among three regions. For the white skip readings, it was more obvious that the R_L values of thermoplastic in mountain area degraded faster than other two regions. The R_L value was higher at the start and then became the lowest in other 4 measurement periods.

Table 5.2. White Edge Thermoplastic R_L Readings

Region	Measure	Time (months)						
		0	6	12	24	36	48	60
Coast	Mean R_L	433	419	393	276	275	289	274
	SD	75	76	100	61	40	63	57
	Sample Size	36	36	34	24	18	18	12
Central	Mean R_L	460	447	392	296	263	268	289
	SD	56	90	100	60	56	55	79
	Sample Size	65	71	65	43	18	12	12
Mountain	Mean R_L	440	366	342	304	259	276	263
	SD	70	52	69	61	66	56	80
	Sample Size	14	16	16	16	12	10	10

Note: R_L is retroreflectivity in mcd/m^2/lux.
SD is the standard deviation.
Shaded cells show increases in the average from the previous time period.

Table 5.3. White Skip Thermoplastic R_L Readings

Region	Measure	Time (months)						
		0	6	12	24	36	48	60
Coast	Mean R_L	431	384	338	286	273	258	238
	SD	75	71	82	80	37	67	54
	Sample Size	23	25	25	14	12	12	6
Central	Mean R_L	459	370	298	264	270	339	310
	SD	52	111	97	42	69	90	84
	Sample Size	50	60	56	43	14	8	8
Mountain	Mean R_L	481	317	293	230	220	232	219
	SD	49	75	76	43	63	49	62
	Sample Size	8	14	14	14	12	10	10

Note: R_L is retroreflectivity in mcd/m^2/lux.
SD is the standard deviation.
Shaded cells show increases in the average from the previous time period.

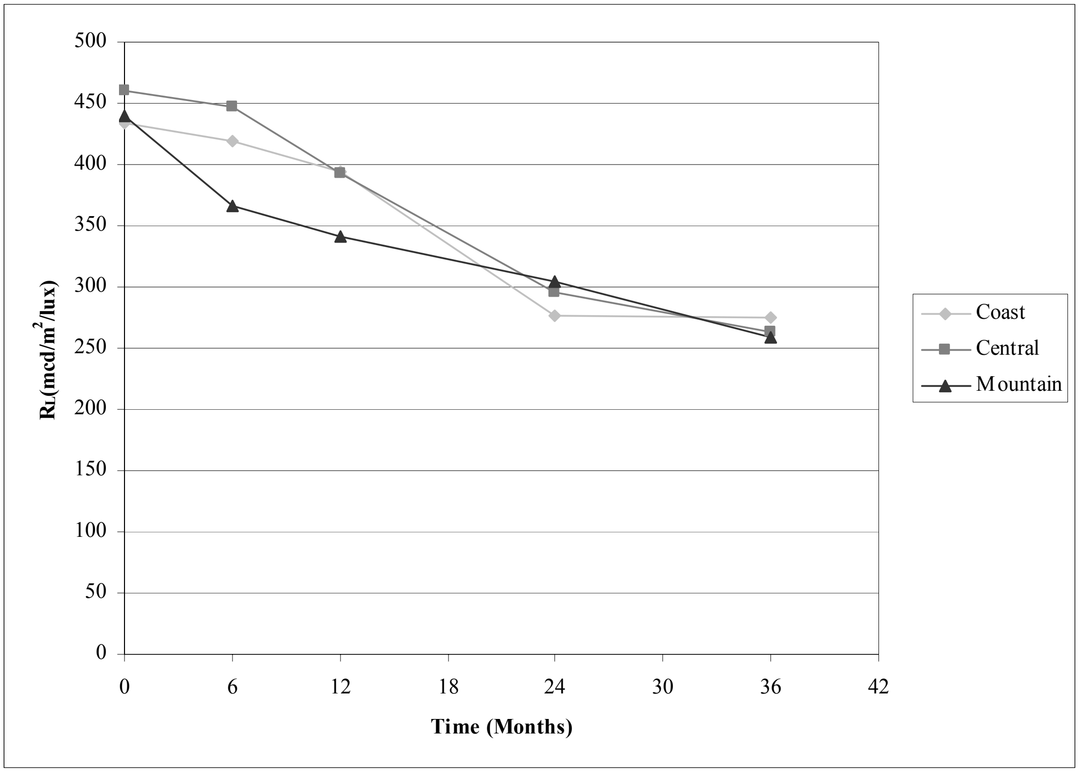


Figure 5.5. White Edge Thermoplastic R_L Readings

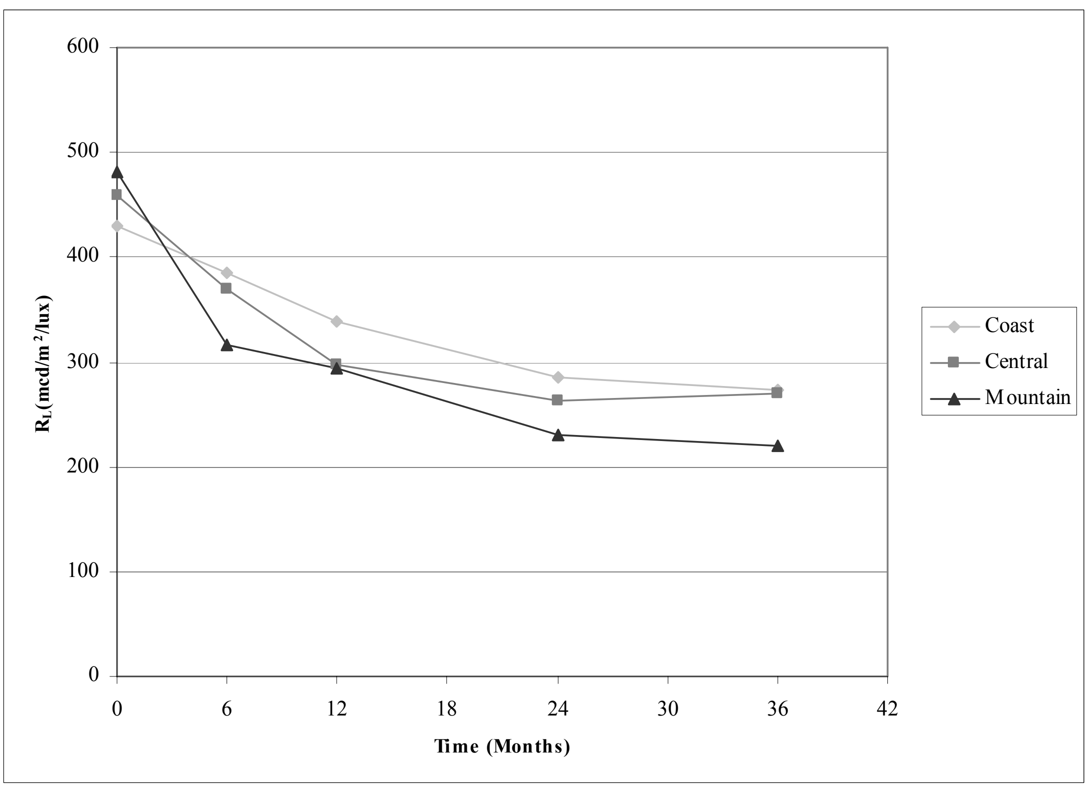


Figure 5.6. White Skip Thermoplastic R_L Readings

5.2.3 ANOVA Analysis of the Collected Retroreflectivity Data

Figures 5.5 and 5.6 show that there may be a difference in the rates of pavement marking retroreflectivity degradation based on the region. An analysis of variance (ANOVA) can establish if the differences measured in the three regions are statistically significant. ANOVA is a statistical procedure for comparing population means. The null hypothesis states that the population means from different populations are all the same. Rejecting the null hypothesis indicates that at least one of the population means differs from the others. A probability of p-value less than α =0.05 indicates that the null hypothesis should be rejected and there is statistical evidence that mean values from different populations are not all equal.

The ANOVAs were conducted at each time period for all data available. The p-values of the ANOVA F-test for white edge and white skip thermoplastics are shown in Tables 5.4 and 5.5. The results show that in only one time period for each marking type there is statistical evidence that mean retroreflectivity values from different regions are not all equal. For the white edge thermoplastics, the time period happened at 6 months (shaded cell in Table 5.4); for the white skip thermoplastics, the time period is at 24 months (shaded cell in Table 5.5). For all the other time periods, there is no statistical evidence that the mean retroreflectivity values from different climate regions differ significantly.

Table 5.4. ANOVA p-values of F Test Results for White Edge Thermoplastics

ANOVA	Time (months)				
	0	6	12	24	36
p-value	0.1171	0.0018	0.1519	0.3043	0.6901
Sample sizes	36/65/14	36/71/16	34/65/16	24/43/16	18/18/12

Note: Sample sizes are for coast/central/mountains.

Table 5.5. ANOVA p-values of F Test Results for White Skip Thermoplastics

ANOVA	Time (months)				
	0	6	12	24	36
p-value	0.06435	0.1094	0.1543	0.0207	0.0538
Sample sizes	23/50/8	25/60/14	25/56/14	14/43/14	12/14/12

Note: Sample sizes are for coast/central/mountains.

The results from the ANOVAs do not show many large differences of the retroreflectivity values because the variation within each regional location is very high. The standard deviation values are in the range of 37-100 as shown in Tables 5.2 and 5.3. The general idea of ANOVA is to compare the variation among regional groups to the variation within groups. If the variation among regional groups is larger than the variation within groups, this provides evidence against the null hypothesis. In this case, the variations within the regional groups are large so that the analysis can not reject the null hypothesis for most time periods.

We observed that in the mountain area the R_L values seemed to degrade faster than in the central and coastal areas. The conclusion drawn from the ANOVA exercise was that the differences of the retroreflectivity values are not statistically significant among three regional locations except in two time periods. In those two time periods, the retroreflectivity values from the mountain area were the lowest. Overall, there is no clear evidence (or the sample size is not big enough) to show statistically significant differences of retroreflectivity values among three regions in most time periods.

5.2.4 Longitudinal Data Analysis

Longitudinal data are data in the form of repeated measurements on the same unit (human, plant, plot, sample, etc.) over time. Retroreflectivity data can be regarded as longitudinal data. To conduct a longitudinal data analysis, we used a formal modeling approach that involves the use of random effects models. Assuming that y_{ijk} represents the retroreflectivity value for road segment k at the jth time period which is measured in the region i, the random intercept model is:

$$y_{ijk} = (\beta_0 + a_k) + (\beta_1 + b_k)Year_j + \beta_2 Location_i + \varepsilon_{i\,jk}$$

Where:

y_{ijk} = Retroreflectivity value in mcd/m^2/lux

$\beta_0, \beta_1, \beta_2$ = The intercept and regression coefficients for Year and Location

$Year_j$ = Time in years, which takes the values 0, 1, 2, and 3

$Location_i$ = The value 1 for coast area, 2 for central, and 3 for mountain area

$\varepsilon_{i\,jk}$ = The residual term

a_k , b_k = The random effects model shifts in intercept and slope

This random effects model requires that the time intervals are equal because measurements closer in time are likely more highly correlated than those taken further apart. Consequently, for the three-year pavement marking retroreflectivity measurements we did not use the values measured at the half-year intervals. Also the model requires that the data should be complete at all time intervals; otherwise, an estimation method should be adopted to estimate the missing data. In our analysis, we only used segments that have complete data, which means that the initial, first year, second year, and third year measurements are all available. The data available are significantly reduced by those requirements. We only analyzed white edge thermoplastic markings because the white center line data were limited. After reducing the data, only 18, 14, and 10 samples in the coast, central, and mountain areas, respectively, were used to conduct the longitudinal analysis.

Figure 5.7 shows the mean retroreflectivity values of each region. The random intercept and slopes model was fit using the “Proc Mixed” procedure in SAS. The model specifies the maximum likelihood estimation method to estimate the covariance parameters. The results are shown in Table 5.7. The t-test indicates that the intercept and year variable are significant in the model.

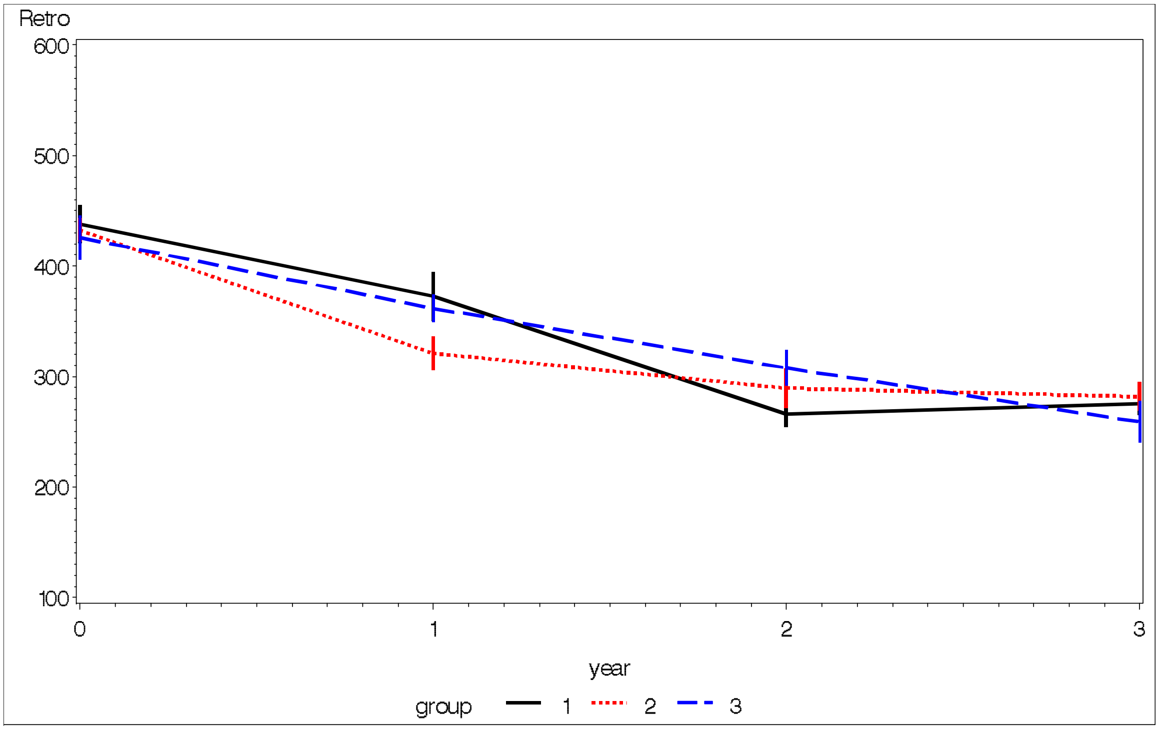


Figure 5.7. Mean Retroreflectivity Data in the Three Areas

Table 5.7. Covariance Parameter Estimates

Effect	Estimate	Error	DF	t-Value	Pr > |t|
Intercept	409.15	13.1194	39	31.19	<.0001
Coast	13.0880	14.4439	84	0.91	0.3675
Central	6.7978	15.1630	84	0.45	0.6551
Mountain	0	-	-	-	-
Year	56.3810	4.0611	41	13.88	<0.001

Table 5.8 shows the effect tests on the location and year variables. The F test results mean that the location variables are not statistically significant and should not be included in the model. In other words, the regional impacts on the retroreflectivity degradation are not significant or the data are not sufficient to provide evidence that regional effects are substantial to the pavement marking degradation. However, the results show that the time factor have a significant impact on retroreflectivity deterioration.

The result from the longitudinal data analysis is similar to that of the ANOVA analysis. Both methods did not find statistically significant evidence that the regional factor has impacts on the white thermoplastic retroreflectivity degradation. However, we observed that in the mountain area the R_L values degrade faster than in the central and coastal areas.

Table 5.8. Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Location	2	84	0.42	0.6587
Year	1	41	192.72	<0.0001

Note: "Num DF" means "Numerator Degrees of Freedom"
"Den DF" means "Denominator Degrees of Freedom"

5.3 Limitations

The above analysis results do not mean that the regional factor does not have any impact on the degradation rate of pavement marking retroreflectivity. This study has several limitations. First, the retroreflectivity data were all collected in North Carolina where the climate variation within the state is much less than the variation between different states. It is possible that the climate factor has greater impacts on the pavement marking performance and the impacts are significant when the difference in the climate becomes larger.

Second, the sample size of this study is relatively small, especially in the coast and mountain areas. With large variances, larger samples are needed to help researchers to draw more meaningful conclusions. Third, the samples used in the comparison were not collected under similar conditions. For example, traffic and road surface (pavement) condition were not considered in the comparison. A study will yield more reliable results if the conditions of the sample road sections are more similar or are at least accounted for.

5.4 Recommendations

This study suggests that a more controlled study should be conducted if we want statistically significant evidence that the regional factor has impacts on the thermoplastic retroreflectivity degradation. A future study should collect data that are almost evenly distributed in the three climate regions. The sample size should not be less than 30 in each region considering the large variations observed in the collected data. The data should be collected on road sections having similar traffic and pavement conditions, or traffic and pavement condition should be measured when marking retroreflectivity is measured.

This study also suggests that it may not be productive to further investigate this subject. The findings presented herein showed that in the mountain area the R_L values degrade faster than in the central and coastal areas though the differences were not statistically significant since the variations within each regional location are relatively large. There are likely other, more important, factors that affect pavement marking degradation rates in NC than location.

6.0 THE IMPACT OF PAVEMENT ROUGHNESS ON PAINT PAVEMENT MARKING RETROREFLECTIVITY

Retroreflectivity is a term used to describe the amount of light returned back to a source, such as the amount of light from a vehicle's headlight that is reflected back towards the driver. The reflected light provides the driver with roadway information and enables a safer drive at night. Retroreflectivity is represented by a measure referred to as the coefficient of retroreflected luminance (RL), expressed in units of millicandelas per square meter per lux (mcd/m^2/lux) [ASTMb 2005]. The current ASTM standard requires that retroreflectometers use a 30-meter geometry [ASTMa 2005].

A Congressional mandate, Section 406 of the 1993 Department of Transportation and Related Agencies Appropriations Act, directed the Secretary of Transportation to revise the MUTCD to include a standard for minimum levels of retroreflectivity that must be maintained for traffic signs and pavement markings [Vereen et. al. 2004]. The minimum retroreflectivity levels and recommended maintenance methods for traffic signs were published in Revision 2 of the 2003 version of the MUTCD. The final rule has been effective since January, 2008 [FHWAa 2007]. The Federal Highway Administration (FHWA) is working with other research agencies to establish a similar minimum retroreflectivity standard for pavement markings. The minimum retroreflectivity requirement for pavement markings is expected to be included in a future version of the MUTCD.

Even though the FHWA is going to publish the minimum retroreflectivity standard for pavement markings, the impacts of many factors on the pavement marking retroreflectivity are unclear or not quantified. This study addresses two of the impacting factors - pavement type and roughness.

6.1 Literature Review

Prior research revealed that many factors might have impacts on pavement marking retroreflectivity values and degradation rates. Those factors include but are not limited to:

- Age of markings, type of pavement marking materials, and marking color;
- Glass bead type, glass bead density, and quality control during marking installation;
- Annual average daily traffic (AADT), type of traffic, heavy vehicle percentages, and road speed limit;
- Pavement type, pavement surface roughness, and roadway geometry; and,
- Weather/climate, snowplowing, salt and sand use, and studded tires.

Several research projects have been conducted to evaluate the impacts of these factors on pavement marking retroreflectivity values and establish degradation models. We review a few of those studies in this section.

Pavement marking age has long been recognized as one of the most important factors affecting pavement marking retroreflectivity degradation. The marking retroreflectivity values decrease over time. If the marking installation and measurement dates are known, the marking ages are easy to calculate. Most previous studies agreed on using marking age as an independent variable in degradation models. What they disagreed on was the form of marking age variable. Some studies assumed that retroreflectivity had a linear relationship with marking age [Lee et. al 1999, Sitzabee et. al. 2009]. Other studies proposed to use exponential transform [Perrin et. al 1998] or logarithmic transform [Andrady 1997] of marking age as an independent variable.

Pavement marking material type and color were normally identified as categorical variables in degradation models. Waterborne paints and thermoplastics were the most commonly used pavement marking types and they make up 59.9% and 22.7% of the total pavement marking mileages in the US [Migletz and Graham 2002]. Other types of pavement marking materials such as epoxy, polyurea, preformed plastics, and polyester were also widely used. The lifecycles and degradation rates of different marking materials varied in a wide range (13). Previous research has shown that white and yellow markings had different levels of retroreflectivity. White markings generally had higher retroreflectivity readings than yellow markings assuming the same materials were applied [Craig et. al. 2007].

Traffic volume (or AADT) was believed by many traffic engineers to have an impact on the marking retroreflectivity values. A recent study included traffic volume as an independent variable in a multiple linear regression model [Sitzabee et. al. 2009a]. Abboud and Bowman [Abboud and Bowman 2002a] proposed a logarithmic model which multiplied the AADT and time and used the result as a variable - vehicle exposure. Vehicle exposure was the estimated total number of vehicles that had passed though the road in each lane since the installation of the new pavement markings. However, the values of traffic volume as a variable were constantly changing and accurate traffic counting data overtime were normally unavailable for most of the roads.

A recent study found that bead density had a correlation with paint marking retroreflectivity readings [Zhang et. al. 2009]. Bead density was defined as the surface percentage of glass beads partially exposed above the paint marking material. Higher bead density led to higher paint marking retroreflectivity readings.

The study presented in this chapter investigated the impact of two new factors, pavement type and roughness, on paint marking retroreflectivity. Paint marking performance was evaluated on two types of asphalt pavements, plant mixed and bituminous surface treatment (BST) pavements. The paint marking performance on these two types of pavements was analyzed separately. The impact of pavement roughness on paint marking retroreflectivity was also investigated in the study.

6.2 Research Objective

The study reported herein was part of an overall research effort to evaluate paint marking performance in NC. While collecting field marking retroreflectivity data on paint markings, the research team observed that pavement markings applied on smooth pavement surfaces generally have higher retroreflectivity readings than on rough surfaces. The observation led to the collection of pavement roughness data and a systematic investigation of its effects on the paint markings retroreflectivity

The pavement type and roughness impacts on paint marking retroreflectivity are important because the same paint markings may have different levels of retroreflectivity readings when they are applied to the pavements with different roughness characteristics. The objectives of the study were to collect pavement marking retroreflectivity data and roughness data, analyze the pavement roughness and marking retroreflectivity readings based on the pavement type, and determine the impact of pavement type and roughness on pavement marking retroreflectivity.

6.3 Research Scope

The scope of this research is focused on the waterborne paint pavement markings applied on two-lane highways with flexible pavements. Water-based paint is currently the most commonly used pavement marking material. Paint is used on almost 60% of the total pavement marking mileages in the US [Migletz and Graham 2002]. In North Carolina, water-based paint markings are reported to make up more than 80% of the total marking mileage [NCDOT 2008]. Normally, paint markings are applied on secondary routes where traffic volumes are relatively low [NCDOT 2008]. This is because paint materials, though they often have lower initial retroreflectivity values and degrade at a faster rate, are less expensive than other marking materials.

Pavement roughness and marking retroreflectivity data were collected on two-lane highways with asphalt pavement and low traffic volumes. The measured roads were paved with asphalt pavements. The data collection efforts were made on two-lane highways because two-lane highways comprise the majority of the highway system. Data collection was also much easier and safer on two-lane highways than on other types. In North Carolina, 74,015 of the total 79,042 roadway miles (93.6%, maintained by the NCDOT) are two-lane highways [NCDOT 2007].

6.4 Methodology

Field marking retroreflectivity values were collected using a handheld retroreflectometer. Pavement roughness data were collected using a high speed inertial road profiler. The collected information was analyzed to determine the impact of pavement type and roughness on marking retroreflectivity.

6.4.1 <u>Data Collection</u>

The pavement marking retroreflectivity data were collected by the NC State research team and the pavement roughness data were collected by the NCDOT Pavement Management Unit. The data collection procedures are described in the following sections.

6.4.1.1 Pavement Marking Retroreflectivity Data Collection

The research team used a handheld LTL 2000 retroreflectometer for data collection. The LTL 2000 retroreflectometer uses 30-meter geometry, which is the geometry required by ASTM Specification E 1710-05 [ASTM 2005]. The standard operating procedure in the instrument manual was strictly followed during field data collection. Field calibration of the LTL 2000 on each site was conducted before measurements were taken. A global positioning system (GPS) device was used to record the coordinates of starting and ending points on each test location.

The paint data were collected on secondary roads in four of the highway divisions in NC. Those roads have low traffic volumes, with annual average daily traffic (AADT) on most roads of less than 4000 vehicles per day. All measured roads were two-lane highways with asphalt pavement surfaces. The research team selected a test location on the road to be measured. Test locations were not selected on sections with sharp horizontal or vertical curves, but were otherwise randomly chosen. Test locations were about 200 feet long.

Twenty measurements, approximately evenly distributed along the 200 foot segment, were taken for each white edge pavement marking line. It is necessary to average numerous instrument readings in each direction on each line to account for variability in retroreflectivity along a line. A previous study found that that paint centerline retroreflectivity values measured in the direction of paint striping are significantly higher than values measured in the opposite direction [Rasdorf et. al. 2009] so the centerlines were measured in each direction. The centerlines on two lane highways could be either solid or skip lines. A total of 20 measurements for solid lines and 10 measurements for skip lines were taken in each direction of each the yellow centerline.

Figure 6.1 shows a typical data collection site layout. Pavement marking retroreflectivity data on one white edge line and two yellow center lines were used in this study. The right wheel track and left wheel track lines illustrate the location where the pavement profile data were collected.

6.4.1.2 Pavement Roughness Data Collection

The international roughness index (IRI) is developed by the World Bank in the 1980s and is widely used in the US for measuring road roughness. FHWA requires state highway agencies to submit roughness measurements in the form of IRI for the Highway Performance Monitoring System (HPMS). IRI defines the characteristic of the longitudinal profile of a traveled wheel track and constitutes a standardized roughness measurement [Sayers et. al. 1986]. The IRI values of roadway pavement are generally in the range of 50-700 inches/mile. Lower values represent smoother pavement surfaces [Sayers et. al. 1986].

Road profile measurements were collected using a high speed inertial road profiler capable of collecting pavement profile data at highway speeds. Figure 6.2 shows the photo of a road profiler. The data from the road profiler were provided by NCDOT in an ERD file format. The data collection road name, start point road name, vehicle travel direction, and end point road name were all recorded during the data collection. The data were collected in one traveling direction along the road and the profiles of both wheel tracks were recorded.

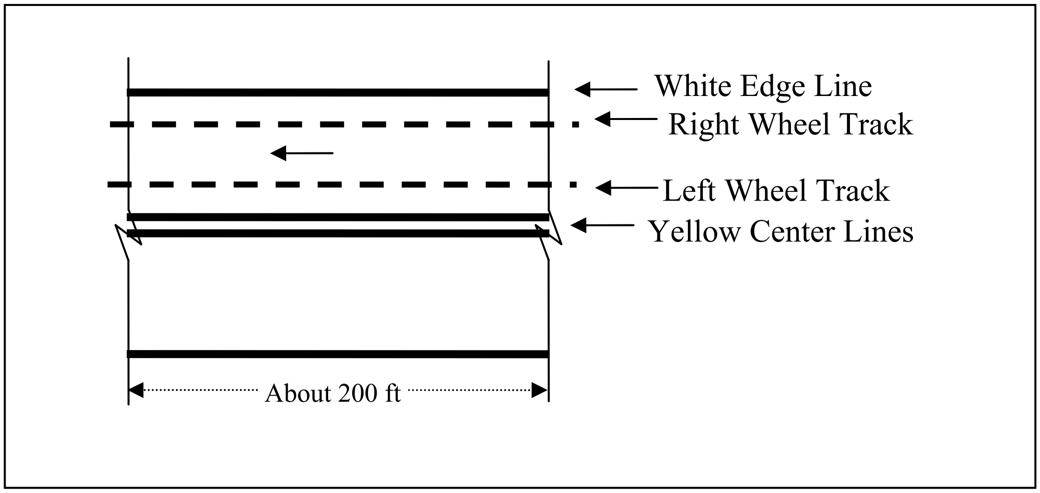


Figure 6.1. Field Data Collection Site Layout

Figure 6.2. NCDOT Road Profiler [NCDOT 2009]

The road profile data were collected in two rounds. The first round of data was collected on January 5, 2009, which included profile readings on 8 roads. The retroreflectivity readings were collected 35-38 days before the profile data collection. The second round of data was collected on May 14, 2009, which included profile readings on 9 more roads. The retroreflectivity readings were collected 6-10 days later.

The ProVAL software was used to computer IRI values from the road profile ERD files. ProVAL software was developed by the FHWA and the Transtec Group [The Transtec Group 2009]. It allows users to view and analyze pavement profiles in different ways. The IRI values were computed for each fixed interval of 200 feet. The 200-foot IRI computing interval was selected to match the approximate length of the retroreflectivity samples. The variations of the IRI values along the road were found to be large. Figure 6.3 shows the IRI readings along a typical road 6500 feet long. The lowest IRI value was 105 inches/mile and highest value was

271 inches/mile in this case. The large IRI variations required a careful selection of the IRI reading of the road section on which retroreflectivity values were measured for accurate analysis.

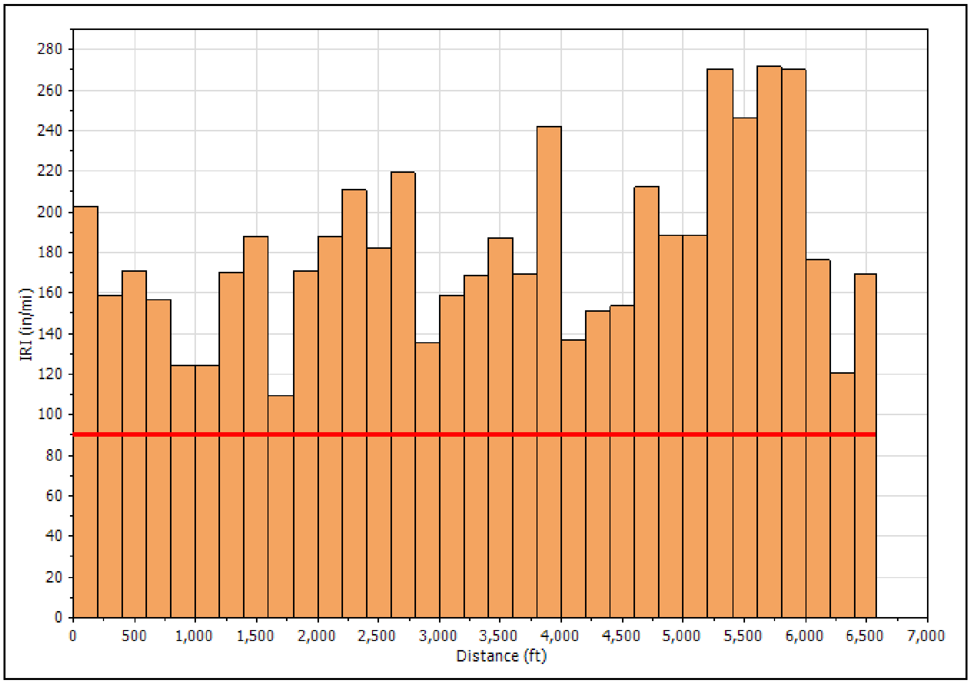


Figure 6.3. IRI Readings along a Typical Road

6.4.2 Pavement Type

The NCDOT pavement management system lists three types of asphalt pavements, plant mixed, bituminous surface treatment (BST), and slurry. The pavement roughness and marking retroreflectivity data were collected on the first two types of pavements. For plant mixed pavements, pavement materials are mixed in a central plant. It offers advantages such as more careful proportioning of the ingredients, more uniform mixtures, and less dependence on favorable weather conditions [Wright and Paquette 1987]. BST, also referred to as chip seal pavement, generally consists of aggregate spread over an asphalt emulsion layer. Plant mixed pavements generally have higher uniformity than BST pavements of the same age and the roughness readings (IRI) on plant mixed pavements are generally lower than BST pavements of the same age.

Figure 6.4 shows typical images of the pavement markings applied on BST and plant mixed pavements. The image on the left shows a BST pavement. The road surface texture appears rough. The image on the right is of a plant mixed pavement and the surface texture is smoother than the BST pavement. The pavement type directly impacts the pavement roughness and, as the image shows, likely affects marking retroreflectivity as well.

Readers should be aware that it is straightforward for an engineer to distinguish a BST and a plant mixed pavement either through a field inspection or examining an image of the pavement surface. We examined the pavement surface images and classified the pavements into BST and plant mixed types for the 17 roads where the roughness readings were measured. The results were exactly same as the pavement types reported in the 2008 NCDOT pavement condition survey.

Figure 6.4. Paint Pavement Markings Applied on BST (left) and Plant Mixed (right) Pavements (Photos by G. Zhang)

6.4.3 Data Matchup

To make valid comparison, the pavement IRI readings need to match up with the marking retroreflectivity readings. A geographic information system (GIS) map was used to determine the distance from the profile measurement start point to the retroreflectivity measurement start point.

Figure 6.4 shows an example of matching up the computed IRI intervals with a retroreflectivity measurement interval. The pavement roughness data and marking retroreflectivity data were collected on the state route SR 1947. The pavement profile measurement start point is at SR 1945 and the end point is at NC 96. GPS coordinates were used to locate the retroreflectivity measurement start point and end point on the GIS map. We measured the distance from the profile measurement start point to the retroreflectivity measurement start point. The distance was 2515 feet. The distance between the retroreflectivity measurement start point to the end point was measured to be 245 feet, which was slightly longer than the planned measurement length of 200 feet. In this case, the retroreflectivity measurement location did not exactly match the IRI fixed intervals. We chose to analyze the mean IRI value of two involved intervals as the IRI value for the retroreflectivity measurement section. The two profile intervals completely overlapped the retroreflectivity measurement interval. In Figure 6.5, the computed IRI values for the right wheel track at the intervals 2400-2600 feet and 2600-2800 feet were 97.10 and 80.45 inches per mile, respectively. The mean IRI value of the two intervals was 88.78 inches a mile which was used as the right wheel track IRI value for the retroreflectivity measurement section.

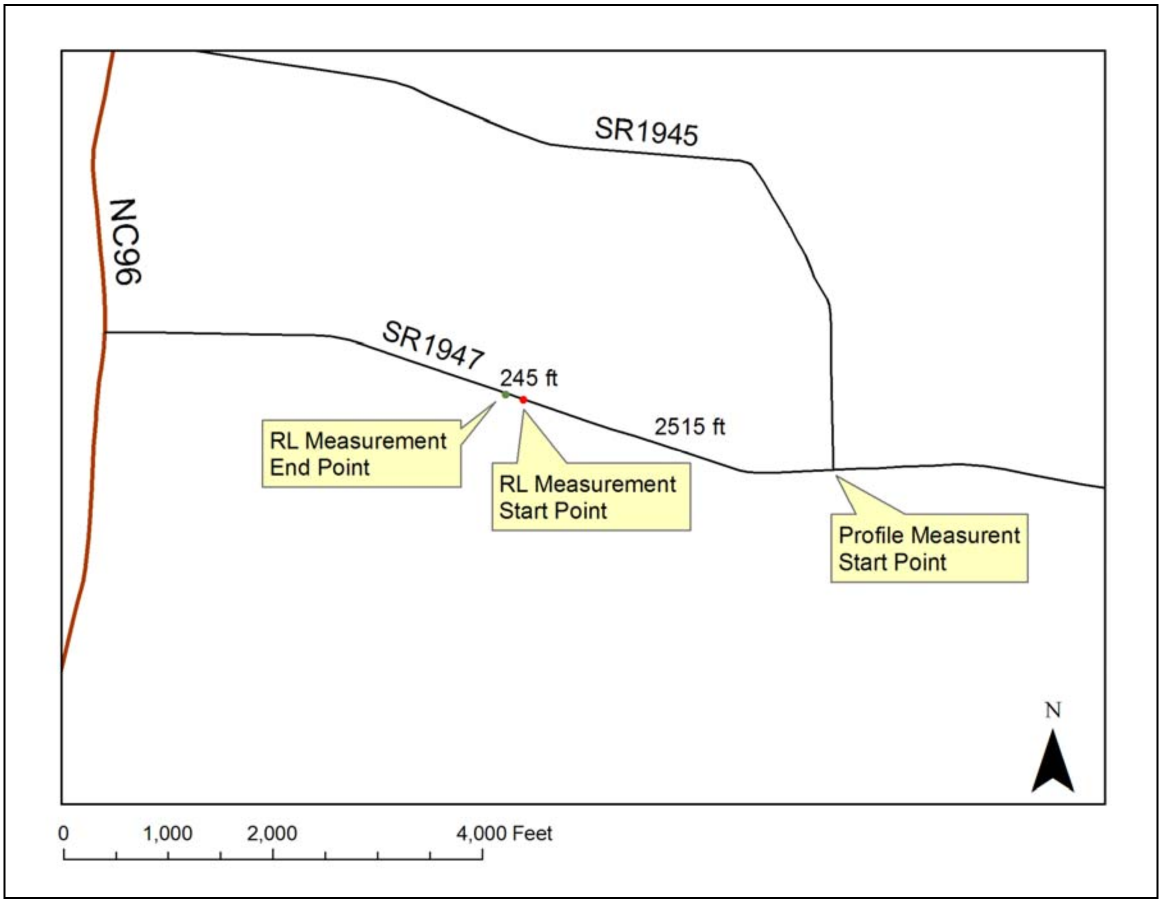


Figure 6.5. Retroreflectivity Measurement Location in a GIS map

6.4.4 Data Characteristics

Tables 6.1 and 6.2 list the marking retroreflectivity readings and pavement IRI readings from the 17 sample road sections. Table 6.1 includes 9 measured road sections on plant mixed pavements and Table 6.2 includes 8 sections on BST pavements. The marking ages are calculated from marking installation date to the R_L measurement date. The R_L measurement date was in the range of 6-38 days from the roughness measurement date.

The R_L readings on two yellow centerlines were measured in both directions of traffic flow. The values listed in the "Yellow Center R_L" column are the mean values of the retroreflectivity readings measured in both directions on the two yellow centerlines. The values in the "White Edge R_L" column are the mean values of the 20 measurements on the white edge marking. The IRI values are the mean values of two fixed intervals as described above.

The retroreflectivity readings on yellow centerlines are lower than white edge lines, which is consistent with other research findings [Craig et. al. 2007]. On plant mixed pavements, the average R_L reading on yellow center markings is 137 mcd/m^2/lux, which is significantly lower than the average R_L reading of 238 mcd/m^2/lux on white edge markings. On BST pavements, the average R_L reading on yellow markings is 89 mcd/m^2/lux, which is also much lower than the 180 mcd/m^2/lux for white markings.

Table 6.1. Marking R_L and Pavement Roughness Reading on Plant Mixed Pavements

No.	Road No.	Marking Age in Days	R_L Measurement Date	Roughness Measurement Date	Yellow Center R_L	White Edge R_L	Left Wheel IRI	Right Wheel IRI
1	SR 1623	448	12/1/2008	1/5/2009	128	243	97.67	84.01
2	SR 1613	440	12/1/2008	1/5/2009	119	310	66.22	86.63
3	SR 1736	1004	11/29/2008	1/5/2009	69	193	105.64	114.97
4	SR 1737	1004	11/29/2008	1/5/2009	136	219	57.79	67.64
5	SR 1947	575	5/20/2009	5/14/2009	169	179	55.81	88.78
6	SR 1382	585	5/24/2009	5/14/2009	156	177	68.37	85.51
7	SR 1008	1038	5/20/2009	5/14/2009	215	322	105.25	145.08
8	SR 1937	1042	5/20/2009	5/14/2009	192	336	87.59	100.07
9	SR 1537	1048	5/20/2009	5/14/2009	49	167	80.03	76.79
Avg	-	-	-	-	137	238	80.48	94.38

Note: The R_L values are in the unit of mcd/m^2/lux
The IRI values are in the unit of inches/mile

Table 6.2. Marking R_L and Pavement Roughness Reading on BST Pavement

No.	Road No.	Marking Age in Days	R_L Measurement Date	Roughness Measurement Date	Yellow Center R_L	White Edge R_L	Left Wheel IRI	Right Wheel IRI
10	SR 1713	442	11/28/2008	1/5/2009	92	243	91.81	156.86
11	SR 1714	442	11/28/2008	1/5/2009	94	131	142.63	131.62
12	SR 1715	438	11/28/2008	1/5/2009	90	218	93.79	156.07
13	SR 1607	438	11/29/2008	1/5/2009	66	171	126.93	206.15
14	SR 1101	591	5/24/2009	5/14/2009	80	186	114.62	134.45
15	SR 1104	587	5/24/2009	5/14/2009	65	139	91.85	168.40
16	SR 1509	579	5/24/2009	5/14/2009	123	234	252.39	215.44
17	SR 2536	1036	5/20/2009	5/14/2009	102	117	198.99	138.27
Avg	-	-	-	-	89	180	139.13	163.41

Note: The R_L values are in the unit of mcd/m^2/lux
The IRI values are in the unit of inches/mile

The retroreflectivity readings on plant mixed pavements were higher than the readings on BST pavements. The result is as expected because the plant mixed pavements generally have smoother pavement surfaces than BST pavements. The average R_L measurements of yellow center marking and white edge markings on plant mixed pavements are 48 mcd/m^2/lux and 58 mcd/m^2/lux higher than on BST pavements, respectively.

The IRI readings show the same pattern as the retroreflectivity readings. Note that a higher IRI value represents a rougher road surface. The average left wheel IRI reading is slightly smaller than right wheel reading, which indicates that the left wheel road surface is smoother than right wheel. The IRI readings on BST pavements are much higher than the readings on plant mixed pavements. The roughness readings are consistent with the observation that BST pavements are generally rougher than plant mixed pavements.

6.4.5 Data Analysis

A statistical test, t-test assuming unequal variances for two groups, was used to determine if the retroreflectivity readings (or roughness readings) measured on plant mixed pavements and BST pavements are statistically significant. The null hypothesis (H0) was that: The mean retroreflectivity readings (or roughness readings) on two types of pavements were equal. The alternative hypothesis (H1) was that: the mean retroreflectivity reading (or roughness readings) on plant mixed pavements were larger (smaller) than the values measured on BST pavements. We used a one-tailed hypothesis test for this specific scenario.

A multiple linear regression model was used to fit the retroreflectivity data and the IRI roughness data. The linear regression model can be expressed as:

$$Y = \alpha + \beta_1 X_1 + \cdots + \beta_n X_n + e$$

Where:

Y = Response variable, R_L values in mcd/m^2/lux

$X_1 \ldots X_n$ = Independent variables

$\alpha, \beta_1 \ldots \beta_n$ = Regression coefficients, estimated from the data

e = Random error with mean zero

The coefficient of determination, R2, is the proportion of the variability in the response explained by the regression model, which was used to determine how well the regression line approximates the real data. The overall range of the R2 value is from 0 to 1.0. A 1.0 R2 value indicates that the regression line fits the data perfectly.

6.5 Results

The t-test was used to test if the yellow centerline retroreflectivity values, the white edge retroreflectivity values, the left wheel IRI values, and the right wheel IRI values measured on plant mixed pavements are statistically significantly different from the values measured on BST pavements. The t-test hypothesized that the mean differences were zero. The one tailed p-values were 0.0157, 0.0288, 0.0132, and 0.0001, respectively for each of the four tests. The p-values were all less than the specified significant level 0.05.

The mean values of the yellow centerline retroreflectivity measurements and the white edge retroreflectivity measurements collected on the plant mixed pavements (137 and 238 mcd/m^2/lux, respectively) were larger than the values collected on the BST pavements (89 and 180 mcd/m^2/lux). The mean values of left wheel IRI values and right wheel IRI values measured on plant mixed pavements (80.48 and 94.38 inches/mi) were also smaller than the values measured on the BST pavement (139.13 and 163.41 inches/mi).

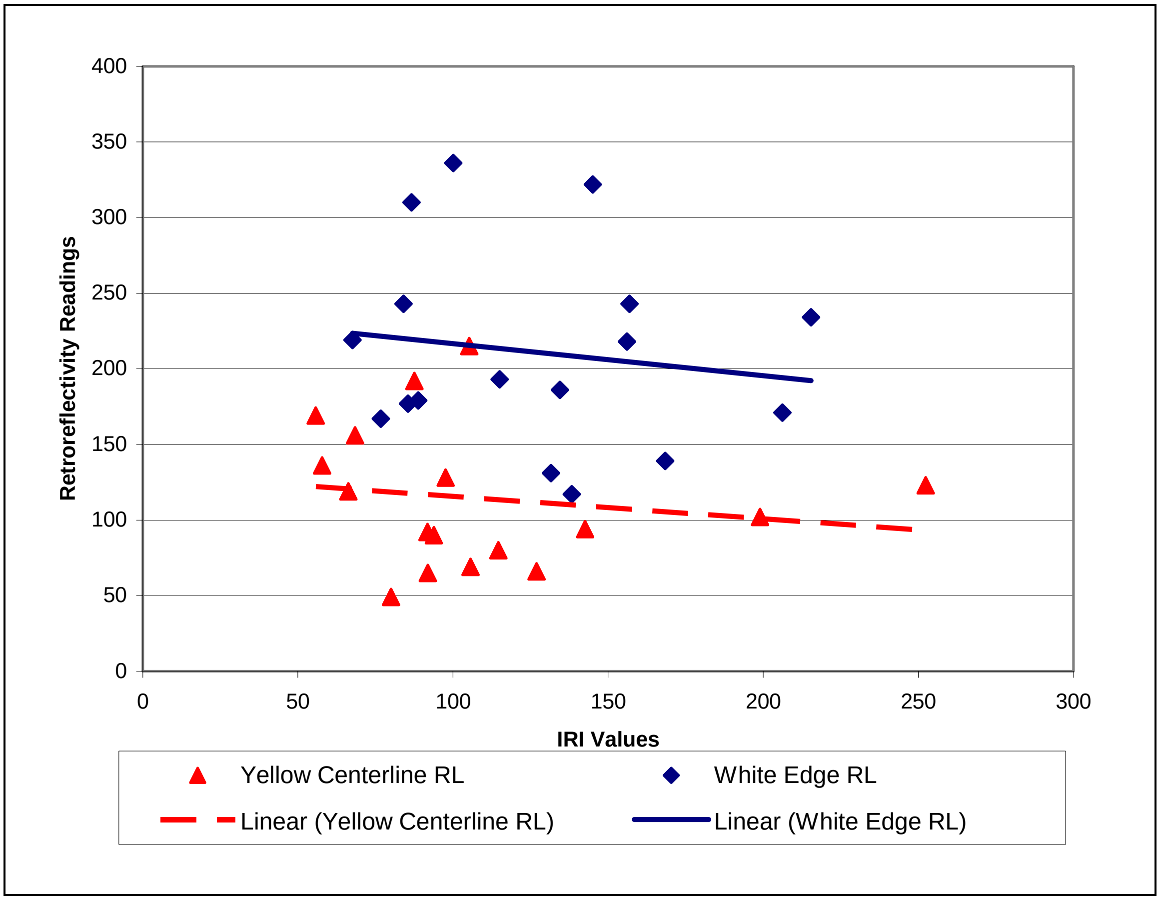


Figure 6.6. Pavement Marking R_L and Pavement IRI Measurements

We used a multiple linear regression model to fit the data. Two variables, marking age and roughness reading, were considered as independent variables in the model. However, the coefficient of the marking age variable was found to be positive (0.020 and 0.043 for white and yellow markings, respectively). This is unexpected; literature shows that the coefficient should be negative, that is, markings generally lose retroreflectivity as they age. The reason might be that we observed large retroreflectivity values on roads 7 and 8 where markings were almost 3 years old. Furthermore, the marking age variable was not found to be significant at a 95% level. Thus, we did not include the marking age variable in the regression model. The linear regression model only included one independent variable - IRI reading.

Figure 6.6 shows the white edge retroreflectivity values plotting against right wheel track IRI values and the yellow centerline retroreflectivity values plotting against left wheel track IRI values. The solid line is the linear regression line for the white edge markings and the skip line is for the yellow markings. The equations of the two lines are:

$R_L = 237 - 0.212$ IRI ($R^2 = 0.021$, White edge line)

$R_L = 130 - 0.147$ IRI ($R^2 = 0.025$, Yellow centerline)

The regression slopes are negative (-0.212 and -0.147) which indicates that R_L values decrease when the IRI values increase. When the IRI values increase 100 inches/mile, the R_L values decrease 21.2 and 14.7 mcd/m^2/lux for white edge markings and yellow center markings, respectively. It means that the R_L values are higher on the smoother roads (IRI values are lower) and are lower on rougher roads (IRI values are higher). The result is same as expected.

The R2 values of the two regression lines are very low (0.021 and 0.025), which means a large portion of the variability in the data is not explained by the regression models. The data in Figure 6.6 also show the variability in the data is large. For example, when the IRI values are around 100 inches/mile, the retroreflectivity readings of white edge markings vary in the range 160-340 mcd/m^2/lux. The large variability in the data indicates that pavement roughness (IRI value) is not the major impact factor that determines the paint pavement marking retroreflectivity values. Other factors (such as bead density) may have more impacts on the retroreflectivity values than pavement roughness.

6.6 Conclusions

The paint markings on plant mixed pavements have higher retroreflectivity values than markings on BST pavements. The pavement roughness readings on plant mixed pavements are lower than that on BST pavements. The research result implies that markings on BST pavements have shorter life cycles than markings on plant mixed. It indicates markings on BST pavements need to be restriped in a shorter time period than markings on plant mixed pavements to maintain the same marking quality.

A common practice of many transportation agencies is to restripe paint pavement markings in a fixed time period such as two years (some states have shorter restriping periods). The research results suggest that paint markings on BST pavements generally have lower retroreflectivity readings than the markings on plant mixed pavements all else being equal. The retroreflectivity values on BST pavements are more likely to fall below a minimum level than on plant mixed pavements. Thus, marking crews should consider applying higher quality paint markings on BST pavements to achieve the same service life as the markings on plant mixed pavement.

As a rule of thumb, a paint truck speed of 10-12 mph will result in a paint thickness of 15-18 wet mils without beads if the paint gun pressure is properly set. Paint markings are typically 15 mils (1 mil = 0.001 inch) in thickness when applied. A slower paint truck speed will lead to thicker paint markings and denser glass beads. The results suggest that on BST pavement roads, the paint truck crew should consider travelling slower than on plant mixed pavement to counter the naturally lower retroreflectivity values. The authors want to point out that many field paint truck crews already know this fact and apply paint markings in this way based on their experience. This study provides field data supporting the practice.

The study also found that pavement roughness has an impact on the pavement marking retroreflectivity readings. Pavement markings on smoother pavements (lower IRI readings) generally have higher retroreflectivity readings than markings rougher pavements (higher IRI readings). However, the pavement roughness is not a dominant factor that determines marking retroreflectivity. The marking retroreflectivity readings vary in a wide range on pavements with similar roughness readings.

7.0 THERMOPLASTIC PAVEMENT MARKING DEGRADATION MODELING AND ANALYSIS

In 1993 the United States Congress directed the Secretary of Transportation to revise the Manual on Uniform Traffic Control Devices (MUTCD) to include a minimum standard of retroreflectivity for pavement markings [Vereen et. al. 2004]. Although no official standards have been published yet, candidate minimum values for road pavement markings have been established [Turner 1998] and the FHWA is expected to publish pavement marking retroreflectivity standards in the near future.

With 78,000 miles of state maintained roads the North Carolina Department of Transportation (NCDOT) is charged with managing over 312,000 lane miles of pavement markings [Howard 2006]. Pavement markings cost NC approximately $14.5 million dollars a year in contractor-performed work [Howard 2006] and much more when one also considers in-house work. The proposed Federal standards are of concern to NC and other states.

The purpose of this chapter is to present the results of an analysis of pavement marking deterioration and the predictive models that were established to determine it. These models can provide NC and other states with new information about pavement marking performance that will focus limited resources where they are most needed and help them avoid replacing materials with effective life still remaining, thus helping them address any new Federal standards in an efficient way.

7.1 Objective and Scope

The objective of this study was to determine the performance characteristics of thermoplastic pavement markings using data from the NCDOT and to create viable life cycle predicative models for those markings. Although the focus of this research was on thermoplastics an evaluation of paint pavement marking materials was also conducted and models were created for the performance of both thermoplastics and paints. Specifically, this chapter:

- Evaluated variables that affect pavement marking service life.
- Created a pavement marking degradation model for thermoplastics and paints.
- Established performance-based level of service increments using the proposed minimum standards and the degradation rates established from the degradation model.
- Predicted the life of pavement markings, based on their deterioration rate and on FHWA/NCDOT minimum levels.

7.2 Background

Understanding retroreflectivity performance over time is important to establishing an optimum pavement marking strategy. This section provides a basic description of pavement marking materials and retroreflectivity measurement, and highlights five previous studies that addressed pavement marking service life.

7.2.1 Marking Materials

According to the American Association of State Highway and Transportation Officials (AASHTO), markings control traffic to encourage safe and expeditious operations [AASHTO 2004]. For highways and streets AASHTO classifies markings into three general types, which are pavement markings, object markings, and delineators [AASHTO 2004]. This research focuses on pavement markings, which AASHTO further defines as center stripes, lane lines, no-passing lines, and edge striping [AASHTO 2004]. In all cases pavement markings refer to long-lines and should not be confused with object markings or delineators. In this study the type of pavement marking is defined by its lateral location on the roadway. Specifically, this study refers to edge lines or "middle lines," where middle lines represent both centerlines and lane (skip) lines.

Pavement markings are sometimes defined by type. Migletz and Graham [2002] listed 16 types of line marking materials available on the market as of 2002. The majority of the materials are defined as durable pavement markings, which simply means that they are expected to last longer than one year. Waterborne and solvent-based paints are typically considered to be nondurable pavement markings. These are expected to have a short service life of one year or less.

The NCDOT primarily uses four pavement marking materials which are paint, thermoplastics, epoxy, and polyurea. Paints make up nearly 60 percent of the pavement marking inventory for the NCDOT while thermoplastics represent another 23 percent [Howard 2006]. In 2003 the NCDOT decided to use polyurea instead of epoxy for concrete applications. Epoxy is still used in some limited applications but is in the process of being phased out of the inventory [Howard 2006].

7.2.2 Retroreflectivity

Pavement marking retroreflectivity is a term used to describe the amount of light returned back to a driver from a vehicle's headlights as it is reflected from the pavement marking. The light provides drivers with critical information about the road and enables the driver to navigate safely at night. National Highway Cooperative Research Program (NCHRP) Project 17-28 concluded that there is no correlation between safety and the level of pavement markings retroreflectivity (Bahar, et al., 2006). Specifically the NCHRP 17-28 study indicated that what is important is the presence of markings but not necessarily whether the marking are "new marking bright" or "old marking bright". The authors state that one hypothesis is that drivers compensate for the different levels by slowing down as the markings decrease in retroreflectivity (Bahar, et al., 2006). The authors also state that the best estimate of the joint effect of retroreflectivity and driver adaption is approximately zero for non-intersection road segments during non-daylight conditions (Bahar, et al., 2006). However, the NCHRP Project 17-28 study confirms that the presence of markings has an affect on safety. Ultimately, retroreflectivity is what makes pavement markings visible at night and the visibility of markings directly relates to driver safety [Al-Masaeid and Sinha 1994].

American Society for Testing Materials (ASTM) standard E1710-05 specifies that pavement marking retroreflectivity should be calculated by measuring the amount of light returned from a pavement marking when a handheld device directs light at the pavement marking. The entrance angle should be 88.76 degrees, which is measured from the reference axis which is a perpendicular line from the pavement surface. Additionally, the returned amount of light is measured at an observation angle of 1.05 degrees. The observation angle is based on a headlight mounting point at 0.65 meters directly over the stripe, and an eye height of 1.2 meters directly over the stripe which is the angle measured from the difference of the vehicle's headlight back to the drivers view from a point 30 meters in front of the vehicle [ASTMa, 2005].

The FHWA has not yet determined minimum retroreflectivity levels. Research recommendations have established three options as shown in Table 7.1 [Turner 1998]. Essentially, the column headings have yet to be finalized. Prior to publication as a standard, the three options will likely need to be reduced to a single definition of roadway classifications and speeds.

Table 7.1. Recommendations for Minimum Retroreflectivity Values [Turner 1998]

Option 1		**Non-Freeway ≤ 45 mph**	**Non-Freeway ≥ 45 mph**	**Freeway ≥ 55 mph**
Option 2		**≤ 40 mph**	**≥ 45 mph**	**≥ 60 mph and ≥ 10,000AADT**
Option 3		**≤ 40 mph**	**45 – 55 mph**	**≥ 60 mph**
With RRPM	**White**	30	35	70
	Yellow	30	35	70
Without RRPM	**White**	85	100	150
	Yellow	55	65	100

Note: Retroreflectivity values are mcd/m^2/lux and measured with 30-m geometry
Adapted from an unpublished report.

The proposed standards are set up as a matrix that accounts for three major variables, which are speed, presence of raised retroreflective pavement markings (RRPMs), and color. The matrix separates roadways with and without RRPMs, and also provides separate standards for white and yellow markings. For example, white pavement markings on a road with a speed limit of 70 mph and without RRPMs would require a value of 150 mcd/m^2/lx, as shown by the shaded portion of Table 7.1.

7.2.3 <u>Previous Studies</u>

Five major studies were reviewed that provide insight into pavement marking retroreflectivity performance. These five studies are by Andrady; Lee, et al.; Migletz, et al.; Abboud and Bowman; and Sarasua, et al. Each of the five studies evaluated pavement marking retroreflectivity performance over time and explored the performance characteristics of pavement markings so that predictive models, service life estimates, or degradation curves could be established. Thus, they are closely related to the work reported here. The researchers recognize that there are many ongoing studies regarding pavement marking retroreflectivity, most of which are focused on the relationship between safety and retroreflectivity. These five studies were the ones in the literature with a primary focus on pavement marking performance and modeling.

7.2.3.1 Andrady

Sponsored by the NCHRP, Andrady [1997] developed one of the first degradation models for pavement marking retroreflectivity. The focus of Andrady's study was to determine the environmental impact of volatile organic compounds and to identify alternative pavement marking materials. Part of Andrady's study was to evaluate the performance characteristics of pavement markings in terms of retroreflectivity. Andrady created the logarithmic model shown below for thermoplastics:

$$T_{100} = 10^{(R_0 - 100)/b} \quad (1)$$

Where:

T_{100} = Time in months for the retroreflectivity to reach 100 mcd/m^2/lx

R_0 = Estimate of the initial retroreflectivity value

b = Gradient of the semi-logarithmic plot of retroreflectivity

The end of service life for this model was defined by reaching a retroreflectivity value of 100 mcd/m^2/lx. No goodness of fit measures have been published for this model.

7.2.3.2 Lee, et al.

In the mid-90's Michigan State University (MSU) evaluated the performance of several pavement-marking materials [Lee, et al., 1999] for the Michigan DOT. Their study sought to provide insight and guidance on how to implement cost effective procedures for pavement marking management. Focusing on four major marking materials (paints, thermoplastics, thermosets, and tapes) the study used 50 sample sites throughout Michigan to determine degradation rates for the various materials and a minimum threshold value of 100 mcd/m^2/lux to indicate satisfactory marking performance.

The measuring device used was the Mirolux 12, which is a 15-meter geometry device. The study reported that there was a great deal of variability in the measurements provided by this device and that any future studies should consider better data collection equipment and methods.

Large variances in service life were reported. Data collection limitations minimized the amount of data that could be compared over time. Although the degradation rates were deemed to be linear, the R^2 values seemed low (R^2 = 0.14), providing little confidence that a linear degradation model was the best fit to the data. Of significant note was the finding that snowfall (snow plowing) was highly correlated to retroreflectivity degradation. Alternatively, Annual Average Daily Traffic (AADT), speed limit, and percent commercial traffic showed no correlation with degradation of retroreflectivity and were eliminated from the model.

The basic conclusions of the study indicated that water-borne pavement markings are the most cost effective type. This conclusion was based on reasonable performance compared to the low cost. Other materials performed better but the cost involved did not justify the improved service life. The model for thermoplastics by Lee, et al. is shown below.

$$R_L = -0.3622*X + 254.82 \qquad R^2 = 0.14 \quad (2)$$

Where:

R_L = Retroreflectivity of pavement marking (mcd/m^2/lx)

X = Age of the pavement marking in days

The end of service life for this model was defined by reaching a retroreflectivity value of 100 mcd/m^2/lx.

7.2.3.3 Migletz, et. al.

The study used regression analysis to evaluate various materials and establish a predictive degradation curve of material performance over time. Marking material type, road surface type, and marking material color were the independent variables evaluated. Conducted by the Transportation Research Board (TRB) using a Laserlux mobile retroreflectometer (model number not specified), this study took place from 1994 to 1998 [Migletz et al. 2001]. Its purpose was to evaluate the life of durable pavement markings. Included in the study, as a benchmark, was some limited evaluation of waterborne paints. The researchers collected data on 362 longitudinal (edge, center, and lane) pavement-marking lines from 85 sites across 19 states.

Results from the regression analysis indicated there was a great deal of variation in the performance of identical materials at different sites. The variation was attributed to differences in roadway type, region of the country, marking specifications, quality control, and winter maintenance. Analysis indicated that yellow lines performed better than white but this was attributed to the use of a lower threshold rather than to superior durability.

A follow up study [Migletz et al. 2001] established a service life matrix that provides degradation rates for each color of each material type sorted by cumulative traffic passages and elapsed months. Cumulative traffic passages are the cumulative sum of the AADT over time. The matrix provides average service lives, standard deviations, and service life ranges in months. The findings for the two most common pavement marking materials are:

- Average life of waterborne white paint markings is 10.4 months
- Average life of thermoplastics is 26.2 months (white) and 27.5 months (yellow)

7.2.3.4 Abboud and Bowman

This study explored the application cost, service life, and user cost related to crashes for pavement marking retroreflectivity for the Alabama DOT. Abboud and Bowman [2002] developed an exponential regression model to depict the relationship between pavement marking retroreflectivity and vehicle exposure (VE). VE is a function of time and AADT. Also unique to this model is the absence of marking color and surface material, both of which have been established as dependent variables for pavement marking degradation in the other four studies cited here. The degradation model presented for paint was:

$$R_L = -19.457 * \ln(VE) + 26.27 \qquad R^2 = 0.31 \qquad (3)$$

The model for white thermoplastic edge lines was:

$$R_L = -70.806 * \ln(VE) + 150.55 \qquad R^2 = 0.58 \qquad (4)$$

Where:

R_L = Pavement marking retroreflectivity (mcd/m^2/lx)
ln = Natural logarithm

VE = Vehicle exposure = AADT * PM_age * 0.0304
AADT = Annual average daily traffic
PM_age = Age in months

7.2.3.5 Sarasua et. al. (2003)

The South Carolina Department of Transportation (SCDOT) supported a research project at Clemson University and The Citadel to evaluate the effective life cycle of pavement marking retroreflectivity over time [Sarasua, et. al. 2003]. The primary research objective was to develop predictive models that could estimate the rate of pavement marking degradation. The models could then be applied in an overall pavement markings management plan.

The project work focused on interstate highways and evaluated pavement marking retroreflectivity performance during a 28-month period. Data were collected 6 times at over 150 sites throughout SC's interstate system. An average R_L value was established from a series of 11 measurements taken with an LTL-2000 at each data collection site for each collection interval. Other retroreflectivity measurement instruments were used during the research but only the data from the LTL-2000 was used in the analysis. Furthermore, the data were collected using 30-meter geometry, which is the required geometry identified in ASTM E 1710-97.

In this study retroreflectivity performance was based on four major independent variables: surface type, marking material, marking color, and maintenance activities. Each variable was analyzed using regression analysis and was compared to the dependent variables. The dependent variables were the differences in retroreflectivity values and the percent differences in retroreflectivity values. Several other variables were considered but only these four were determined statistically to be viable independent variables that affected the performance of pavement markings over time. Traffic volume was one variable that was initially thought to impact performance but was later eliminated. Traffic volume was inversely correlated to the dependent variables and was thought to be adequately accounted for by the variable "time".

Sarasua, et al. developed two types of models for each combination of marking material, surface material, and color. One model was non-linear and represented the initial "break-in" period while the second model was linear and represented the degradation of the pavement marking retroreflectivity after the break-in period. The models were developed for thermoplastics and epoxy. The thermoplastics on asphalt models are shown below. The end of service life for this model was defined by reaching a retroreflectivity value of 100 mcd/m^2/lux.

Model for white thermoplastics:	Diff = -0.06*(Days) – 6.80	$R^2 = 0.47$	(5)
	% Diff = -0.03*(Days) – 3.29	$R^2 = 0.39$	(6)
Model for yellow thermoplastics:	Diff = -0.03*(Days) – 3.63	$R^2 = 0.21$	(7)
	% Diff = -0.02*(Days) – 2.35	$R^2 = 0.24$	(8)

Where:

Diff = Difference in retroreflectivity over time
% Diff = Percentage of difference in retroreflectivity over time
Days = Time in days

7.2.4 Summary of Literature

This literature review presented the existing knowledge base in the field of pavement marking retroreflectivity performance modeling. Table 7.2 shows a summary of the five studies reviewed. There are large differences in the degradation models between the different research efforts. Three of the five studies concluded that pavement markings degrade linearly while two concluded that they follow a logarithmic decay model.

Table 7.2. Summary of Modeling Studies

Research Sponsor	Year	Authors	Model Type	R^2	Marking Material
NCHRP	1997	Andrady	Logarithmic	Unavailable	Unavailable
MSU	1999	Lee, et al.	Linear	0.14	Thermo
TRB	2001	Migletz, et al.	Linear	Unavailable	Paint & thermo
Alabama DOT	2002	Abboud & Bowman	Logarithmic	0.31 - 0.58	Paint & thermo
SCDOT	2003	Sarasua, et. al.	Linear	0.21 - 0.47	Thermo
Thermo: thermoplastics					

Another finding is that none of the previous efforts examined the impact of lateral line location on the overall performance of a given pavement marking. Logically, the performance of a line should depend on its lateral placement, since some lines like lane lines are typically hit by vehicles more often than other lines like edge lines.

7.3 Methodology

This section presents the methodology used for data collection and analysis in this study. The data used for this study were collected by an independent contractor who was originally hired by the NCDOT to measure retroreflectivity for specified NC roads for the purpose of quality assurance for new markings. Since the researchers did not have control over the data collection methodology there were some limitations on the analysis associated with using the existing data. Fortunately, some of the data were useful for this purpose. For most of the results reported herein the available data set was reduced to roads that used thermoplastic pavement markings. Furthermore, for the initial analysis, only those roads that had been under observation for a full five years were used. Limited data were available for analyzing paint based pavement markings.

Least squares analysis was employed as the modeling method. A range of possible variables was evaluated for inclusion in the model, but only those variables with a significant impact on the degradation of pavement markings were kept in the model.

7.3.1 Data

The retroreflectivity data for this study were collected via a modified Laserlux mobile retroreflectometer (model LLR5) mounted on a Chevy Suburban. According to Lundkvist and Isacsson [2007] vehicle-mounted retroreflectometers are preferred because they allow a technician to safely collect a large amount of data at highway speeds. The alternative to the mobile collection device is a handheld unit, like the LTL-2000 that was used in other studies. NCDOT's decision to use the mobile device enabled the safe and efficient collection of a large amount of data.

The data were collected using the standard 30-meter geometry required by ASTM. The R_L readings are averaged for every tenth of a mile and recorded in the onboard computer. The R_L value has units of mcd/m^2/lx and is an average of all the valid scans recorded for a tenth-mile road segment. The data collected for thermoplastics included 56 segments that represent approximately 450 miles of roadway. The data collected for paints included 37 segments that represent approximately 300 miles of roadway.

Vehicle-mounted devices are subject to errors from variations in the vehicle suspension and in the roadway surface. Current standards are not published for mobile collection devices; however, the calibration process used throughout data collection minimized these errors. Prior to a data collection trip the Laserlux unit was calibrated with a known test bed of pavement markings at the fleet's maintenance facility. The test bed was comprised of pavement markings with known retroreflectivity values that were established using the LTL-2000 hand held device. The LTL-2000 calibration process met the ASTM standards required for pavement markings retroreflectivity. Using the known test bed, established with the LTL-2000 handheld device, enabled the technician to calibrate the mobile device. The calibration process accounted for errors due to changes in vehicle load, tire pressure, and ambient light. In the field a handheld LTL-2000 was used to make sure that the Laserlux mobile device stayed calibrated to handheld standards. Calibration was performed in the field on each collection segment and during collection when conditions changed.

7.3.2 Minimum Standard

Establishing a minimum standard for pavement marking retroreflectivity is a key step in determining its service life. This study used a classification system based on the level of service (LOS) concept to identify the current condition of pavement markings as well as to determine the expected lengths of their service lives. The LOS increments and NC minimum standards are derived from existing pavement marking specifications for retroreflectivity [Sitzabee, 2008]. The LOS is separated into durable (thermoplastics) and nondurable (paints) since each have a different application within the state of NC based on the roadway's AADT.

Table 7.3 shows the LOS increments used in this research. The left columns show the increment values for thermoplastic markings and the right columns show the increment values for paint markings. All values are in mcd/m^2/lx. The red LOS, shaded in Table 7.3, indicates the minimum standard for retroreflectivity that was used in this study and is the basis for defining the end of service life condition.

Table 7.3. LOS Increments and NC Minimum Retroreflectivity Standards

LOS	Thermoplastics		Waterborne Paint	
	White	Yellow	White	Yellow
Blue (A)	≥ 275	≥ 210		
Green (B)	200-274	145-209	≥ 250	≥ 215
Yellow (C)	175-199	125-144	150-250	115-215
Amber (D)	150 - 174	100 - 124	100-149	65-114
Red (F)	≤ 149	≤ 99	≤ 99	≤ 65

7.3.3 Modeling the Data

The researchers used Jump software to develop a degradation model for the data. Both continuous and categorical data were considered in fitting the model to the data. The analysis for thermoplastics on asphalt included 56 road segments all of which had a full five years of available retroreflectivity data that were collected at the following increments: 0, 6, 12, 24, 36, 48, and 60 months. The data set included pavement marking retroreflectivity values, time, initial retroreflectivity, AADT, geographical region within NC, line width, line thickness, and snowplow activity. Values for these variables, including their ranges, are given in the "Variables" section below.

A stepwise selection process was used in developing the model. Each candidate variable was inserted into the model one by one and checked. Only those variables that reached a level of significance greater than 95 percent were left in the model. Once the variables were defined the candidate model was developed and evaluated based on R^2.

A linear regression model makes two major assumptions. The first major assumption is that the responses are independent and normally distributed. A Q-Q plot is a method used to check that this assumption is true. A Q-Q plot is a graph of the residuals plotted against a set of percentiles of the standard normal distribution. Under the assumption of normality, the Q-Q plot should approximate a straight line.

The second major assumption is that the population variances are equal. A plot of the residuals against the predicted values is used to confirm this assumption. The residual plot of the predicted values is a graphical representation of the offset of each value. The desired outcome is an even distribution of residuals around the mean value. A consistent pattern that shows equal offsets is expected if the variances are equal. However, the equal variance assumption is often violated because the variances typically increase or decrease with the expected response, showing a cone shape in the plot of the residuals.

7.4 Results

A detailed evaluation of the variables that affect the degradation of pavement markings was conducted. This section presents the results of these studies for both thermoplastics on asphalt and for paints. Based on the models the researchers found that pavement marking R_L degraded linearly for the first five years of its life cycle. To obtain the service life the linear degradation was extrapolated to the point where the curve reached the defined end state. The assumption is that the material would not subsequently change the nature of the degradation pattern and would remain linear for the remainder of the life cycle. This was considered a conservative assumption consistent with the literature. Recall that three of the five studies presented earlier were linear and two were logarithmic. If the degradation was in fact logarithmic beyond the range of this database, this would result in an even longer service life.

7.4.1 Variables

During stepwise selection the F-statistic was used to check the effect of each candidate variable on the model. A forward stepwise selection was performed where the model starts with one independent variable and the effect was checked using the F-statistic. During each step forward the researchers added and checked a new independent variable. If the variable passed the effects test it was retained in the model. If it failed the variable was removed from the model. The researchers repeated this process until all the variables had been checked.

Retroreflectivity (R_L) was chosen as the dependent variable. The results of the effects test for the consolidated model are summarized in Table 7.4, which shows that time, the initial R_L value, AADT, line type, and color each significantly affected the model.

Table 7.4. Effects Test for White Edge Using the F-Statistic

Variables	Sum of Squares	F Ratio	Prob > F
Time	535700	189	< 0.0001
Initial R_L	129090	46	<0.0001
AADT	73461	26	<0.0001
Line Type	102641	36	<0.0001
Color	43318	15	0.0001

The researchers believe that the snowplow, region, line width, and line thickness variables could have an impact on pavement marking performance to some extent and checked each of those. However, each of the variables was not considered statistically significant. The lack of statistical significance for these variables is attributed to limitations in the data and not necessarily because of a lack of impact on degradation. Further explanation of each variable in the model is presented below.

For the effects test the null hypothesis (H_0) stated that the impact of the variable on the degradation of pavement marking retroreflectivity was insignificant. The alternative hypothesis (H_a) stated that the impact of the variable on the performance of pavement marking retroreflectivity was statistically significant. A probability of F-value less than $\alpha = 0.05$ indicates that H_0 should be rejected in favor of H_a and the variable should be kept in the model because there is statistical evidence that the variable impacts the performance of pavement marking retroreflectivity. As a final step in evaluating the variables the correlation of all the combinations of variables was checked and none were above $|0.5|$.

The independent variables included in the model for thermoplastics were:

1. Time – is a continuous parameter and is the most significant variable affecting degradation of pavement marking retroreflectivity. All pavement-marking studies reviewed included time as the most significant variable affecting retroreflectivity degradation. Time is measured in months from marking installation. The points of time that were modeled were 0, 6, 12, 24, and 60 months.
2. Initial R_L value – is a continuous variable measured in mcd/m^2/lx. This variable is the initial value of retroreflectance and is measured within the first 30 days of application of the marking. Tables 7.5 and 7.6 illustrate the values of initial R_L used in this study for both thermoplastics and paint. The mean, standard deviation and range of R_L values are given.

Table 7.5. R_L Summary Statistics for Thermoplastics on Asphalt

Time (months)	Mean R_L (mcd/m^2/lx)	R_L Standard Deviation (mcd/m^2/lx)	R_L Range of Values (mcd/m^2/lx)
0	365	103	168 - 563
6	324	82	201 - 473
12	319	85	163 - 488
24	235	75	110 – 443
36	212	67	93 - 383
48	223	62	88 - 364
60	222	75	98 - 389

Table 7.6. R_L Summary Statistics for Paint

Time (months)	Mean R_L (mcd/m^2/lx)	R_L Standard Deviation (mcd/m^2/lx)	R_L Range of Values (mcd/m^2/lx)
0	222	60	75-348
6	202	56	71-332
12	172	57	67-364

3. AADT – Annual average daily traffic is a continuous parameter that measures the volume of traffic on the roadway in vehicles per day. Sarasua, et al. [2003] argued that AADT was not significant and was accounted for as a function of time. However, we included AADT as a candidate variable because of the previous report by Abboud and Bowman [2002] which indicated that AADT had a significant impact on pavement marking degradation apart from time.

   The reader should note that AADT is not used as a variable in the paint model. This is because the paint AADT ranged from 200 - 50,000, a variance which caused it to fall out of the model. The paint data was also limited to contractor performed painting that was installed in non-typical applications of AADT > 4,000. Thus, it was not deemed to be generally representative.

For thermoplastics we acquired actual AADT values from the NCDOT for the year 2006. The AADT range was 2,500 – 50,000. The mean and standard deviation were 21,102 and 17,300, respectively.

4. Line Type – also called lateral location – is a categorical parameter that is defined by the transverse position of the pavement marking on the roadway. This variable was included because of the intuitive perception of different vehicle wear attributed to the location of the line on the roadway. This parameter has two positions: edge lines or middle lines. For the purpose of this study centerlines and skip lines were combined into a single category called middle lines. This was done since both types are in a wheel path.
5. Color – is a categorical parameter that defines the color of the pavement marking material. In this study color is either white or yellow.

The AADT and initial R_L variables warrant more discussion. First, an estimate of AADT is usually available for most roads. The AADT values used in this model were 2006 and were used with the understanding that the changes from year to year are minor. Future studies would enhance the model by tracking the actual AADT per year along with the R_L value recorded. Even though this is a limitation in the current model and contributes to some unknown error the effect on the overall model should be small since the coefficient for this variable was small. Additionally, the AADT values are not updated by the NCDOT every year for every road, and even when available by year often have large errors. Still, when using the model to predict future R_L values a forecasted AADT value could be used to increase the quality of the predicted life cycle of the pavement marking.

The initial R_L variable can be handled two ways in the model. NCDOT required that the initial R_L values meet a minimum specification value. Analysts can then use the model along with the initial specification values for R_L in predicting the pavement marking lifecycle. This would be useful in a large majority of the cases where the initial values are not known. However, use of actual initial R_L values would give analysts a better prediction of the lifecycle and is highly recommended in future studies.

7.4.2 Models

This section shows the results for the models developed for thermoplastics and paints. The thermoplastic model is presented first followed by the paint model. In each case a summary is presented of the candidate model. Next, an explanation is presented of the statistical checks used to validate the linear regression assumptions. Finally the models are summarized and an estimated service life is presented for both thermoplastic and paint pavement markings.

7.4.2.1.1 Thermoplastics

There were a total of 336 observations recorded for all thermoplastics on asphalt. All of the thermoplastics applications followed NCDOT specifications and were contractor-installed using a ribbon-extrude technique. In most cases the thermoplastic material uses a standard bead size with a refractive index of 1.50 or greater. The specification calls for seven pounds of beads for every 100 square feet of thermoplastic. In some cases large beads were used but NCDOT discourages their use.

A general linear model was developed for thermoplastics on asphalt based on the variables that were validated by the effects test (time, initial R_L value, AADT, color, and lateral location). However, the reader is cautioned not to extrapolate the model beyond the bounds of the data. The thermoplastic model produced an R^2 equal to 0.60 which was considered to be good compared to previous studies reviewed in the literature. Table 7.7 shows a summary of the parameter estimates for the model and gives the standard error, t-ratio, and Probability > |t| values. The model was:

$$R_L = 190 + 0.39*R_{L\ Initial} - 2.09*time - 0.0011*AADT + 20.7*X_1 - 20.7*X_2 + 19*X_3 - 19*X_4 \quad (11)$$

Where:

R_L = Retroreflectivity in mcd/m^2/lx
$R_{L\ Initial}$ = Initial retroreflectivity in mcd/m^2/lx
time = time since installation in months
AADT = Annual average daily traffic in vehicles per day
X_1 = 1 if edge line, 0 otherwise
X_2 = 1 if middle line, 0 otherwise
X_3 = 1 if white line, 0 otherwise
X_4 = 1 if yellow line, 0 otherwise

Table 7.7. Consolidated Model Parameter Estimates

Estimator	Estimate	Std. Error	t Ratio	Prob>|t|
Intercept	190.7	17.7	10.18	<0.0001
R_L Initial	0.385	0.057	6.75	<0.0001
Time	-2.090	0.152	-13.75	<0.0001
AADT	-0.00113	0.0002	-5.09	<0.0001
X_1	20.7	3.44	6.02	<0.0001
X_2	-20.7	3.44	6.02	<0.0001
X_3	19.0	4.85	3.91	0.0001
X_4	-19.0	4.85	3.91	0.0001

Figure 7.1 shows a residual plot for the model's predicted values. The desired effect is to have an even distribution of the residuals around the mean value which is represented by the horizontal line at zero. The plot shows a fairly distributed set of residuals about the mean indicating that the variances are consistent across the population of predicted R_L values.

Figure 7.2 shows the q-q plot of the model's residuals. The plot clearly shows a straight-line pattern. A straight-line pattern is a visual cue that the distribution is normal. A Shapiro-Wilk goodness of fit test is a statistical check that can determine if the distribution can be assumed to be normal. In a Shapiro-Wilk test the null hypothesis states that the population is normal and that any value below 0.05 would support rejecting the null hypothesis. In this case the probability of P < W equaled 0.2142, providing statistical evidence to keep the null hypothesis and assume that the distribution is normal. This is an important step in validating a regression model since the model relies heavily on the assumption of normality.

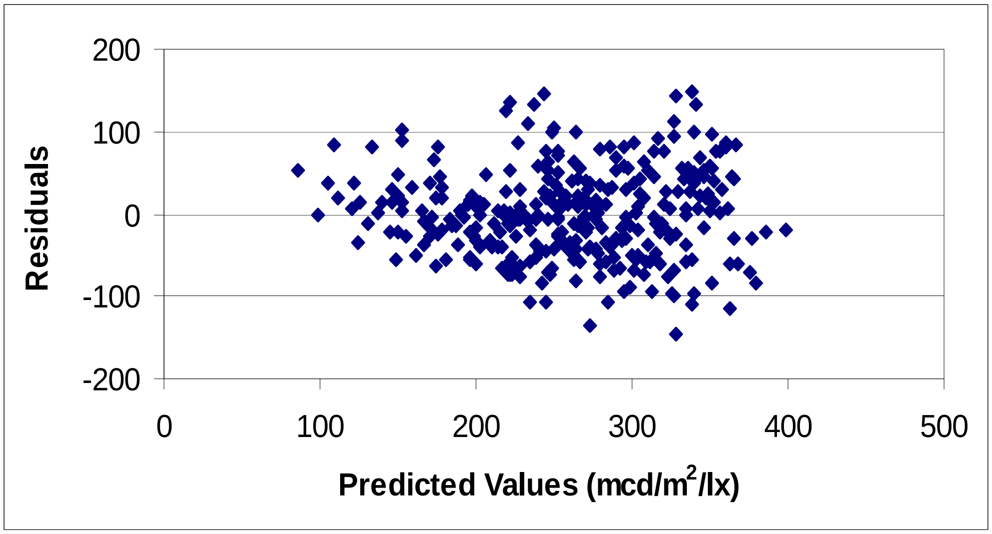


Figure 7.1. Thermoplastic Model Residual Plot of Predicted Values

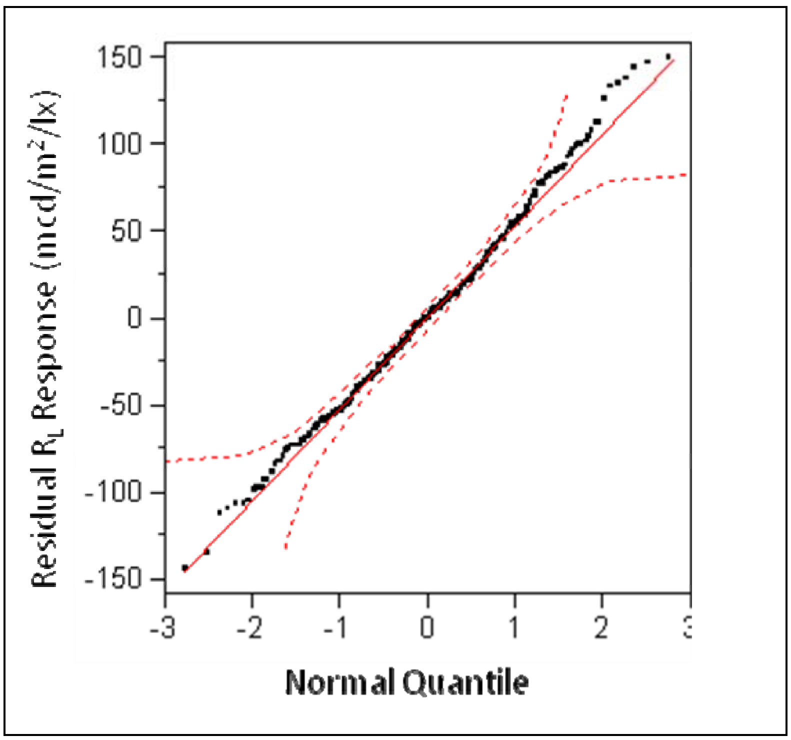


Figure 7.2. Thermoplastic Model Q-Q Plot

7.4.2.1.2 Paints

Before this project, the NCDOT believed that paint markings had a limited service life of approximately one year. This belief was based in large part on the Migletz, et. al. [1999] study which found a mean life of a paint marking to be approximately 10 months. The intent of the NCDOT in collecting paint data was therefore entirely for quality assurance, the data were not intended for analysis, and only a limited number of data points were collected for paints.

However, because paints make up nearly 60 percent of the pavement markings on the roadways in NC, an evaluation of the available paint data was performed during this research.

There were 37 road segments that had a full year of available data. The data were collected for paint at the initial, six-month and one-year points. The data collected included R_L values, initial $R_{L,}$ time, road surface, material, color, and lateral location. The data collected for paints were for roads that were marked by contractors and therefore had to meet the minimum specification required by the NCDOT. All of the paints follow a specification using the same paint material manufactured by the NC prison system. The paint specifications call for a standard size bead with a refractive index of 1.50, and beads are applied at a rate of six pounds per gallon of paint. It is important to note that the model developed in this study was from contractor-installed paints but the majority of paint operations in NC are performed in-house.

The paint model is a general linear model for all paints on both asphalt and concrete. An effects test, using the F-statistic, was performed. The test revealed that the only important variables for this sample were initial R_L and time. Lateral location, color, surface material, AADT, snowplow, thickness, and width were all ruled out by the effects test using the F-statistic. The pavement marking retroreflectivity degradation model for paint is:

$$R_L = 55.2 + 0.77*R_{L\ Initial} - 4.17*time \qquad (12)$$

Where: R_L = Retroreflectivity in mcd/m^2/lx
$R_{L\ Initial}$ = Initial retroreflectivity in mcd/m^2/lx
time = Time after installation in months

Table 7.8 shows the summary of the parameter estimates and gives the standard error, t-ratio and Probability > |t| values. The R^2 (0.75) and adjusted R^2 (0.75) values for the paint model were considered to be very good.

Table 7.8. White Middle Paint Parameter Estimates

Estimator	Estimate	Standard Error	t Ratio	Prob > |t|
Intercept	55	12.0	4.58	<0.0001
R_L Initial	0.769	0.045	19.97	<0.0001
Time	-4.17	.606	-6.89	<0.0001

Figure 7.3 shows a residual plot of the model's predicted values. Unlike thermoplastics the distribution of residuals about the mean for paints is not as equal as desired and begins to show a fan-like pattern as shown by the two dashed lines in Figure 7.3. This would indicate that a transformation should be explored.

Figure 7.4 shows the Q-Q plot of the paint residuals. The plot shows a straight-line pattern, which supports the conclusion that the residuals are normally distributed. However, the pattern does deviate slightly at the ends indicating that another distribution may be appropriate. As such, the researchers also performed a Shapiro-Wilk test on the paint data. The test revealed that the P < W value was equal to 0.0414. This value is below the desired value of 0.05 and would suggest rejecting the null hypothesis that the distribution is normal.

Because of the fan-like shape in Figure 7.3 and the null hypothesis being rejected by the Shapiro-Wilk test, the researchers performed a log transformation of the data and attempted to fit a new model. The Q-Q plot for the model using the log-transformed data looked similar to that of Figure 7.3, and the Shapiro-Wilk test for this new model resulted in a P < W value equal to 0.0133. This gave evidence that a log transformation was not the right solution. Exponential and polynomial transformations were also tried with ineffective results. One possible cause of the questionable normality in the data is that this model combines the paint color and lateral location data into a single model.

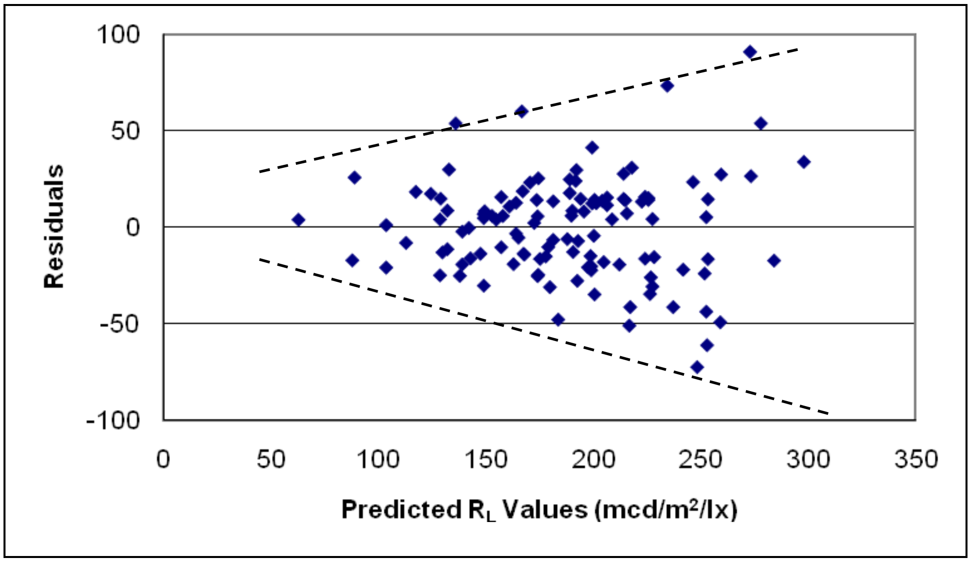


Figure 7.3. Residual Plot of the Predicted Values for Paints

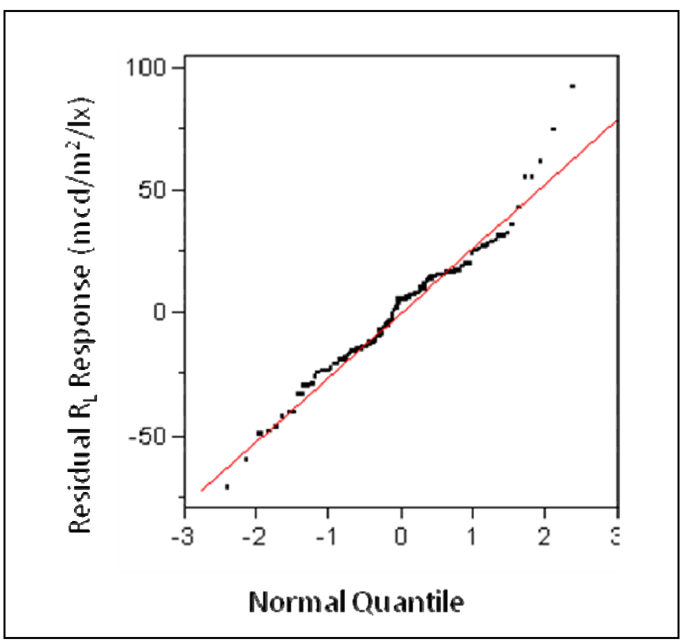


Figure 7.4. Q-Q Plot for Residuals of Paints

As a result of the failing transformations, our best estimates for paint markings remain based on the linear model. The important finding with this model is that after two years the majority of paint markings were still above LOS F, suggesting that paints in NC typically have a service life of two years or more.

7.4.2.1.3 Validation

A good way to validate a model is to reserve data from the original collection and then compare those points to predictions from the developed model. This was considered early on in the research, but the limited amount of data in some areas would not allow for a random removal of the reserved data without negatively impacting the modeling effort. It was evident that additional data would need to be collected in order to validate the model.

On September 18th and 20th of 2007 we collected additional data for the purpose of validating the thermoplastic and paint models previously established. A one-mile road segment was identified for both thermoplastics and paint. The thermoplastic segment had an eight year old white edge line and five year old yellow center and white skip lines. The paint segment had a two year old segment of white edge line and yellow centerline. A sample of 35 retroreflectivity readings was collected from each segment. The 35 readings were taken along the one mile section of road at random points selected by a random number generator.

Table 7.9 shows the estimates from the model and summaries of the validation data. Since the initial R_L values were not known for the road segments the average value for initial R_L from the database was used. The predicted estimate was very close to the mean of the field measurements for white thermoplastic and paint pavement markings. The model was within one unit of predicting the actual value for paint. In each case except yellow middle markings the predicted value was within one standard deviation of the mean of the field measurements.

Table 7.9. Predictive Estimate Compared to Summary of Validation Data

Therm oplastic Line Type	Time (Months)	AADT (vpd)	Initial R_L (mcd/m^2/lx)	Estimated Value from Model (mcd/m^2/lx)	Validation Segment Mean (mcd/m^2/lx)	Validation Segment Lower CI (mcd/m^2/lx)	Validation Segment Upper CI (mcd/m^2/lx)	Validation Segment Standard Deviation (mcd/m^2/lx)
White Edge	96	22000	423	169	156	144	169	37
Yellow Middle	60	22000	286	112	167	158	176	26
White Middle	60	22000	423	204	199	188	209	30
Paint	24	1300	225	128	127	111	143	67

In the fourth case in Table 7.9, the prediction for yellow middle markings was outside the 95 percent confidence interval ("Lower CI" and "Upper CI" in Table 7.9) and close to two standard deviations away from the mean of the measured values. However, it is important to note that during the collection of the yellow middle validation data the researcher observed a section of the markings that had clearly been overlaid with new material. It is possible that the time used to make the yellow middle model prediction was not accurate, or at least not accurate for a portion of the one-mile road segment. Validation of yellow middle values is a limitation of this study. Further validation in future studies is desired overall but specifically warranted for yellow middle markings.

7.4.3 Service Life

This study presented pavement marking degradation models for thermoplastics and paints. The models yielded degradation rates of 2.09 mcd/m^2/lx per month for thermoplastics and 4.17 mcd/m^2/lx per month for paints. With these rates and the designation of minimum standards of retroreflectivity, service lives can be estimated as shown in Table 7.10.

Column one of the Table 7.10 shows the individual category, color, and material of the pavement marking. Columns two and three show the minimum required retroreflectivity value required by NCDOT for the marking to be useful and the initial specification value, respectively. Columns three and four show the resulting service life for pavement markings in months and years. Note that an AADT of 10,000 was used to estimate the generic service lives in Table 7.10. For more accurate service life of pavement markings on a given road segment, the actual initial R_L value recorded and the forecasted AADT could be used. It is important to remember, as noted above, that the service life predictions go beyond the range of data for the model but the values are considered viable for making management decisions.

Table 7.10. Summary of Thermoplastic Pavement Marking Service Life by Category

Category	Minimum Standard (mcd/ m^2/lx)	Initial Specification Value (mcd/ m^2/lx)	Estimated Service life (Months)	Estimated Service Life (Years)
White Edge Thermoplastics	150	375	102	8.5
White Middle Thermoplastics	150	375	84	7.0
Yellow Edge Thermoplastics	100	250	85	7.1
Yellow Middle Thermoplastics	100	250	65	5.4
White Paints	100	225	31	2.6
Yellow Paints	65	200	26	2.2

7.5 Conclusions

In the literature review five studies were identified that have developed various pavement marking degradation models. Three of the five studies concluded that pavement markings degrade linearly while two studies suggest a logarithmic decay. This study confirmed that both thermoplastics on asphalt and paint pavement markings could be modeled as linear through 60 months for thermoplastics and through 12 months for paint.

An alternative logarithmic decay degradation model for paint was also developed and tested. However, the coefficient of determination dropped and the residual plots showed no improvement in the distribution of variances compared to the original linear model, so it was deemed unhelpful. Polynomial and exponential forms were checked and found to be unhelpful as well.

Specifically for markings in NC this study determined:

1. For an AADT of 10,000 vehicles per day, the expected service life for thermoplastics on asphalt ranges from 5.4 years to 8.75 years depending on the color and lateral location (see Table 7.10).
2. Paints have a service life slightly greater than two years (see Table 7.10).
3. Both thermoplastic and paint pavement markings were found to have a far greater life expectancy then originally expected.
4. Lateral location is a key independent variable in modeling thermoplastic pavement marking degradation.
5. AADT had a small but significant impact on the degradation of thermoplastic pavement markings.

The service life of paint pavement markings turns out to be a significant finding. In NC, paints are typically managed on an annual cycle because the assumption is that their service life is approximately one year. The predictive model for paints estimates a mean service life of more than two years. This has critical budget implications for pavement marking managers. It is important to note that the data used for developing the service life was from contractor-performed work. As such, in house marking operations would need to meet the same initial specifications required for contractors in order to achieve the same two year service life.

We have also verified that pavement markings located in the travel path (either center or skip) lines will degrade faster than pavement markings located at the edge of the pavement. This study confirms the findings about the impact of lateral line location on pavement marking degradation from earlier research [Craig, et al., 2007]. The discovery of the impact of lateral location as an independent variable affecting pavement marking degradation adds significantly to the existing pavement marking knowledge base and needs to be considered in both modeling and management of pavement markings.

Finally, there have been conflicting findings about the impact of AADT on pavement marking degradation. Sarasua, et al. [2003] found that AADT was not a significant factor whereas Abboud and Bowman [2002] found that AADT and time both contribute to the degradation of pavement markings. This study found that, for NC data, AADT and time both significantly impact the degradation of thermoplastic pavement markings.

7.6 Future Research

It is highly recommended that additional studies of the degradation rates of other pavement marking materials, including polyurea and resin-based paints, be undertaken. Additionally, further study should be undertaken with respect to the effects of snow plowing on pavement markings. The NCDOT does not have to do a lot of snow plowing on its roads, and the data collected for this variable in this study were categorical, meaning that only a yes or a no was recorded if a road segment was plowed. A future research effort should collect continuous data on snow plowing, recording the number of times a year that a road segment is plowed and then exploring the impact that plowing has on pavement marking degradation.

Paints make up the overwhelming majority of pavement markings and warrant further study. This research was limited in the amount of paint data collected since the study used existing data from contractor-installed paint collected only at the initial, six-month, and one-year increments. The limited data contributed to the general form of the paint model. We recommend analysis of paint data from in-house installations, more segments, over longer time periods (0 to 24 months and beyond), and with more frequent collection. Tests for normality in the data suggest that the paint data in this study came from different populations. Future research should focus on exploring the development of individual models based on color and lateral location categories.

There is clear evidence to support the inclusion of color and lateral location as variables in the paint model. Future research should collect the appropriate data and explore this as well as the other variables that are suspected of impacting degradation but were not statistically significant in the models presented here.

8.0 LINEAR MIXED EFFECTS MODELS FOR PAINT PAVEMENT MARKING RETROREFLECTIVITY DATA

During daytime, drivers discern pavement markings mainly by the color contrast between the marking and the pavement surface. Alternatively, nighttime visibility of pavement markings is generally determined by the retroreflectivity of the pavement marking. Retroreflectivity describes the amount of light returned back to a driver from a vehicle's headlight as it is reflected back from the markings. The reflected light provides the driver with roadway information and enables a safer drive at night. Retroreflectivity is represented by a measure referred to as the coefficient of retroreflected luminance (R_L) and is expressed in units of millicandelas per square meter per lux ($mcd/m^2/lux$) [ASTMb, 2005]. This chapter discusses how to model paint marking retroreflectivity degradation over time.

Retroreflectometers are used to measure pavement marking retroreflectivity. These instruments can be divided into two categories, handheld and mobile. A handheld retroreflectometer is a portable instrument that can be operated by a technician. It is used to test locations on the pavement marking one at a time. A mobile retroreflectometer, on the other hand, is mounted on a vehicle and can measure pavement marking retroreflectivity continuously at normal driving speed. The American Society for Testing Materials (ASTM) has published a specification for using handheld retroreflectometers, while the specification for mobile instruments is still under development [ASTMa, 2005].

Pavement markings can reach the end of their service lives because of bead loss (resulting in poor retroreflectivity), loss of the marking material, marking color change, or loss of contrast between marking and pavement. Daytime visibility and nighttime visibility are normally related to each other. When markings are chipped or abraded by traffic there typically is not only a loss of marking material (which decreases the daytime visibility of the markings) but also a loss of beads (which reduces the nighttime retroreflectivity of the markings) [Migletz and Graham 2002].

Many factors may have impacts on the rate of pavement marking retroreflectivity degradation including, but not limited to:

- Traffic volume (AADT), type of traffic, heavy vehicle percentages, and road speed limit.
- Age of markings, type of pavement marking material, marking color, glass beads type, glass beads density, and quality control during installation.
- Type of pavement and roadway geometry.
- Weather and climate, snowplowing, salt and sand use, and studded tires.

However, it is impossible to incorporate all of these factors into a mathematical model to predict pavement marking performance because not all of them can be accurately measured and recorded over time. Normally a pavement marking degradation model includes a limited number of parameters from the above list.

8.1 Scope

The scope of this research is on waterborne paint pavement marking retroreflectivity. Waterborne paint is currently the most commonly used pavement marking material in the US. Paint is used on almost 60% of the total national pavement marking mileage [Migletz and Graham 2002]. In NC, however, waterborne paint markings are reported to make up more than 80% of the total marking mileage [NCDOT 2008]. Thus, a model for paint pavement marking performance is critical.

The data collection efforts undertaken for this study were made on two-lane highways because these roads comprise the majority of the highway system. Additionally, traffic control for data collection (for safety) was much easier on two-lane highways than on other types of highways. In NC, 74,015 of the total 79,042 roadway miles (93.6%) are two-lane highways [NCDOT 2007]. This chapter does not address paint pavement markings on multi-lane roads or divided highways, but in NC these types of roads often get a different and more durable type of markings anyway.

8.2 Objective

The objective of this research was to develop an accurate paint pavement marking retroreflectivity performance prediction model to be used as a key component in an overall pavement marking management system. An accurate prediction model can help pavement marking managers optimize restriping programs, thereby providing motorists with roadways that have better markings while saving money.

Other researchers have used several forms of degradation models on pavement marking retroreflectivity data, but none of them can predict marking performance satisfactorily at an individual road level. Linear mixed effects models (LMEMs) have been used to predict individual conditions of a transportation asset [Yu et. al. 2007]. The results of work by others in using LMEMs show that they have significantly higher accuracy than other prediction models. One element of the study reported herein was to investigate whether LMEMs can be used to model pavement marking retroreflectivity data and to determine if LMEMs provide more accurate prediction than existing forms of marking retroreflectivity degradation models.

8.3 Literature Review

In this section, we divide degradation models into three categories and analyze their characteristics. We compare the reported modeling methods and point out their advantages and disadvantages.

8.3.1 Linear Regression Model

A simple linear regression model assumes a linear relationship between the mean response and the value of a single independent variable. It can be expressed as follows:

$$Y = \alpha + \beta X + e$$

Where:

Y = Response variable, normally the R_L value in mcd/m^2/lux

X = Predicting or independent variable, normally the time in months or days since installation

α, β = Regression coefficients, usually estimated from a set of data

e = Random error which is a random variable with mean 0

Lee et. al. [1999] evaluated the performance of several types of pavement marking materials in Michigan. The research objective was to determine the degradation rates for the various materials. The study used 50 sample sites throughout Michigan. The data were collected during a 40-month period from March 1994 to July 1997 using a 15-meter geometry device, a Mirolux 12 (as opposed to the 30-meter devices that are standard now). Simple linear regression models were established for polyester, paint, and thermoplastic pavement markings. The coefficients of determination (R^2 values) were in the range of 0.14-0.18, which is low.

Sarasua, et. al. [2003] conducted a modeling study using field data collected from 149 sample sites on interstate routes in SC. The data were collected during a 28-month period from May 1999 to September 2001. Each sample site was measured six times at approximately four to six month intervals. Data used for analysis were collected with an LTL 2000, a 30-meter instrument. The marking materials examined in the study included epoxy, thermoplastic, and preformed plastics tape. The response variable in the simple linear model was the difference between their current measurement and their first data collection measurement. The R^2 values were in the range of 0.21-0.78.

The degradation rates in Sarasua's study were not consistent with Lee's results. For example, the degradation rates of thermoplastics were found to be -0.03 mcd/m^2/lux per day and -0.06 mcd/m^2/lux per day for yellow and white markings in Sarasua's study. The rate was -0.36 mcd/m^2/lux per day in Lee's study. The inconsistency of the research results between the two studies may be attributed to geographic differences (MI vs. SC), measurement instrument differences (Mirolux 12 vs. LTL 2000), and marking material differences (materials were from different vendors). In any case it is a significant difference.

The advantage of simple linear regression is that the model is easy to understand and easy to use. The disadvantage of the simple linear regression model is that only one factor, marking age, is included in the model.

In most situations, the response variable can be predicted more accurately on the basis of a collection of independent variables rather than on one variable as in the simple linear regression model. In a multiple linear regression model, the response variable Y is related to k independent variables:

$$Y = \beta_0 + \beta_1 X_1 + \cdots + \beta_k X_k + e$$

Where:

Y = Response variable, normally the R_L value in mcd/m^2/lux

X_i = Predicting variables, which could be time, AADT, color, initial R_L, and other factors (i = 1, 2, …, k)

β_i = Regression coefficients, usually estimated from a set of data (i = 0, 1,…, k)

e = Random error which is a random variable with mean 0

Sitzabee et. al. [2009a] established multiple linear regression models for thermoplastics and paints using a large retroreflectivity dataset collected in NC. The data were collected over a seven-year period. The data collection instrument was a Laserlux mobile retroreflectometer. They developed a number of multiple linear regression models that had three independent variables (time, initial R_L, and AADT). The initial R_L variable reflected the quality of the initial installation of the markings on a specific road. The R^2 values were in the range of 0.38-0.60.

When including the initial R_L as an independent variable, multiple linear regression models can increase the accuracy of predicting future R_L values for a specific road. However, all linear regression models have an assumption that data collected at different time intervals on the same pavement marking are independent of each other. This assumption is not true for data collected through repeated measurements on the same site. This will be discussed further in the marking retroreflectivity data characteristic section below.

8.3.2 Exponential and Logarithmic Models

Linear regression models assume that pavement marking R_L values deteriorate linearly with time meaning that the degradation curve is a line and the degradation rate is a constant. However, pavement marking R_L values are generally recognized to degrade faster in the first few months after installation. The degradation rates then generally decrease with time. Both exponential and logarithmic models can reflect this degradation trend. Therefore, it is worthwhile to investigate them. The exponential or logarithmic model can be described as:

$$Y = \alpha + \beta \ln X + e$$

or

$$Y = \alpha + \beta e^{X} + e$$

Where:

Y = Response variable, normally the R_L value in mcd/m^2/lux

X = Predicting or independent variable, normally the time in months or days

α, β = Regression coefficients, usually estimated from a set of data

e = Random error which is a random variable with mean 0

Andrady [1997] proposed a logarithmic degradation model in NCHRP Report 372, though the main objective was to assess the environmental friendliness of pavement marking materials. The model is similar to a simple linear regression model except that the logarithmic transform of time is used as an independent variable. The data used in the study were from AASHTO Alabama and Pennsylvania test decks. No goodness of fitness values were published for the model.

Perrin et. al. [1998] established an exponential degradation model based on the data collected by a mobile retroreflectometer in Utah. The retroreflectivity data were collected in five days on markings of various ages. The exponential model for preformed plastics (tapes) achieved an R^2 value of 0.58. However, the models for paint and epoxy markings had very low R^2 values of 0.005 and 0.03, respectively.

The logarithmic model proposed by Abboud and Bowman [2002] multiplies the AADT and time and uses the result to estimate vehicle exposure. Vehicle exposure is the estimated total number of vehicles that have passed along the road since the installation of the new pavement markings. The model assumes that the retroreflectivity value is a function of vehicle exposure. Normally time (age of marking) is used as the independent variable in most other models. A Mirolux 12 was used to collect the retroreflectivity data. A total of 4,518 retroreflectivity measurements were collected at 827 test sites along 520 miles of rural highways in Alabama. The R^2 values were 0.58 and 0.31 for thermoplastics and paints, respectively.

The disadvantage of the exponential and logarithmic models is similar to that of a simple linear regression model. These models include only one factor, either marking age or vehicle exposure. The established models discussed so far only reflect the average marking performance at a population level. However, the model predictions at an individual road level are not necessarily accurate.

8.3.3 Other Models

A number of other types of models have recently been developed using pavement marking retroreflectivity data. Those models are relatively new compared with the two types of models discussed above.

Zhang and Wu [2005] used smoothing spline and time series to model pavement marking retroreflectivity changes over time. Data from the 2002 National Transportation Product Evaluation Program (NTPEP) were used for model development and model validation. The study concluded that both models performed well and that both models can predict the retroreflectivity of a pavement marking material for the next 6 months with very good accuracies [Zhang and Wu, 2005]. The authors pointed out that the data from NTPEP test decks may not be truly representative of actual field installed longitudinal edge lines or skip lines. Readers should also be aware that most marking lines are transversely installed on NTPEP test decks. The performance of those markings could be quite different from the longitudinal markings actually installed on the roads.

Sathyanarayanan et. al. [2008] used the Weibull analysis method to model pavement marking retroreflectivity degradation in Pennsylvania. Weibull analysis is a method typically used in reliability engineering. The model was based on paint data collected from the Pennsylyania NTPEP test deck from July 2002 to July 2005. The established model is similar to an exponential model and includes only time as the predicting variable. This Weibull analysis method predicts a survival probability of pavement markings instead of producing a future retroreflectivity value. The probability result is reasonable from an engineering point of view.

The Sathyanarayanan and Zhang and Wu studies mentioned above possess a common limitation. It has to be recognized that the NTPEP test decks differ significantly from field installed roadways and exposure conditions. As a consequence, the research results cannot necessarily be deemed to be directly applicable. This leaves the research community in a position of choosing between NTPEP data and initiating costly field data collection efforts independently. The authors again call for an evaluation of the NTPEP program to see if changes could be made to better serve the research community and, ultimately, to attain safer roadways.

8.3.4 LMEM

Researchers have developed linear mixed effects models (LMEMs) for predicting individual pavement conditions [Yu et. al. 2007]. This type of model may apply well to pavement marking data. Pavement marking retroreflectivity data are similar to pavement condition data. The data are in the form of repeated measurements on the same road over time. In statistics, data in the form of repeated measurements on the same unit (road) over time are called longitudinal data [Davidian 2005]. The pavement marking retroreflectivity data collected in this study are typical longitudinal data and, therefore, longitudinal data analysis techniques (LMEM is one of these) are applicable and most well suited to the marking retroreflectivity data we collected. In the following sections, we discuss the nature of pavement marking retroreflectivity data, show when LMEMs are suitable models, and develop LMEMs for the marking data.

8.4 Pavement Marking Retroreflectivity Data

In this section, we first discuss the field data collection and the data sampling method. Then, we use paint marking data on two lane highways to illustrate the characteristics of retroreflectivity data for pavement markings.

8.4.1 Data Sampling Method

ASTM Specification E 1710-05 provides a method of measuring pavement marking retroreflectivity using a handheld retroreflectometer that can be placed on the road marking [ASTMa 2005] to obtain R_L measurements. However, it does not specify the sampling method to be employed when using a handheld unit to measure retroreflectivity values. Instead, the number of measurements to be taken at each test location and the spacing between test locations is to be determined by the user. ASTM E 1710 recommends use of the sampling method in ASTM Specification D 6359 [ASTMa 2005]. However, the ASTM D 6359-99 specification was withdrawn in December 2006 because the sampling methods were not being used [ASTM 2008]. Thus, there is no current specified standard sampling method when using a handheld instrument to measure retroreflectivity values. For this study, we generally followed or exceeded the precedent set in Iowa, one of the leaders in pavement marking management in the US. Iowa researchers collected retroreflectivity samples once every 5 miles along a road unless conditions changed. Each sample consisted of an average of 5 measurements over a minimum segment length of 160 feet [Hawkins et. al. 2006].

The purpose of the data collection activity in this study was to provide a sample with which we could evaluate field paint marking performance. The research team first selected sections of the road to be measured. Test locations were not selected where there were sharp horizontal or vertical curves, but were otherwise randomly chosen. Test locations were about 200 feet long. Twenty measurements, approximately evenly distributed along each 200 feet segment (at approximately 10 feet intervals), were taken for each white edge pavement marking line.

A previous study found that that paint centerline retroreflectivity values measured in the direction of paint striping are significantly higher than values measured in the opposite direction [Rasdorf et. al. 2009]. Thus, centerlines were measured in both directions of traffic and their values (2 lines, 2 directions) were averaged to obtain a final R_L for both lines. The centerlines on two lane highways could be either solid or skip lines. A total of 20 measurements for solid lines and 10 measurements for skip lines were taken in each direction for each yellow centerline.

8.4.2 Data Collection Procedure

The study described herein used a handheld LTL 2000 retroreflectometer for data collection. The LTL 2000 retroreflectometer uses 30-meter geometry, which is the geometry required by ASTM Specification E 1710-05. The researchers followed the standard operating procedure in the instrument manual strictly during field data collection. Field calibration of the LTL 2000 was conducted before measurements were taken. The calibration was performed at each site prior to the start of data collection. We used a Global Position System (GPS) device to record the coordinates of the starting and ending points on each test location. Measurement sections were marked with spray paint on the pavement (their boundaries were marked) so that future measurements were taken in the same road section. .

We collected paint retroreflectivity data on secondary roads in four divisions of the NCDOT. Those roads have low traffic volumes, with annual average daily traffic (AADT) on most roads less than 4000 vehicles per day. All measured roads were two-lane rural highways with asphalt pavement surfaces (both chip sealed and plant mixed pavement). Included in the study were 25 roads which were painted in September and October 2007 and measured four times in November 2007, May 2008, November 2008, and May 2009. A two-person team carried out the data collection and each round of data collection lasted about two weeks. NCDOT provided the paint marking installation dates before the field data collection effort was undertaken.

8.4.3 Paint Retroreflectivity Data

The data for the two white edge lines (or two yellow centerlines) located on a single road were averaged to a single value (20 measurements in 200 feet along each line). That value represents the retroreflectivity of both white edge lines on the measured road section. The data from one white edge line (or one yellow centerline) were not considered to be an independent sample because the retroreflectivity values of the two white edge lines (or the two yellow centerlines) on the same road were related to each other. All markings on a road section were normally striped using the same paint truck and the same material batch on the same day by the same marking crew. Columns 2-9 in Tables 8.1 and 8.2 show the retroreflectivity measurements and marking ages for white edge and yellow center markings on the 25 roads, respectively.

Figure 8.1 shows the plots of the retroreflectivity data on the 25 sample roads for white edge and yellow center markings. Plots like Figure 8.1 are called spaghetti plots in a longitudinal data analysis context [Davidian 2005]. The horizontal axis represents the age of the markings in days. The vertical axis represents the retroreflectivity values on a sample road section. The thin lines represent pavement marking retroreflectivity trajectories for individual roads. The bold line represents the average retroreflectivity of all measurements.

Table 8.1. White Edge Pavement Marking R_L Data

	First Round		Second Round		Third Round		Fourth Round		LMEM Model	
No.	Age (Days)	R_L	Age (Days)	R_L	Age (Days)	R_L	Age (Days)	R_L	Intercept	Slope
1	51	239	238	237	436	219	596	187	269	-0.147
2	51	244	237	210	435	230	599	181	264	-0.144
3	86	333	273	298	471	*	635	*	351	-0.225
4	87	282	273	250	471	#	635	145	302	-0.224
5	70	185	253	128	448	99	613	68	190	-0.180
6	71	358	253	262	448	245	613	213	348	-0.232
7	69	382	249	245	442	228	607	163	353	-0.287
8	69	221	249	235	442	184	607	162	257	-0.159
9	71	338	245	288	438	254	603	204	347	-0.230
10	63	331	245	193	438	165	602	133	297	-0.262
11	63	441	245	316	440	284	605	234	415	-0.295
12	70	368	243	310	439	*	603	*	372	-0.245
13	52	379	224	301	419	303	582	271	376	-0.210
14	51	240	224	189	419	130	584	113	239	-0.205
15	49	247	229	195	428	185	591	175	253	-0.157
16	45	269	225	212	424	199	587	156	272	-0.190
17	52	344	217	272	417	265	579	225	341	-0.211
18	52	415	217	339	416	342	575	221	413	-0.279
19	58	355	223	323	423	286	585	233	369	-0.228
20	73	286	227	274	425	278	592	232	317	-0.159
21	72	259	226	247	424	264	591	245	291	-0.121
22	72	378	226	320	424	323	591	246	388	-0.230
23	70	129	224	125	422	126	589	99	161	-0.105
24	35	337	190	250	388	222	555	187	318	-0.233
25	49	211	204	218	402	168	560	147	238	-0.161
Mean	**62**	**303**	**234**	**249**	**431**	**227**	**595**	**184**	**310**	**-0.205**

* Data are missing due to pavement resurfacing and marking restriping.
# Circumstances prevented the collection of these data.
R_L and Intercept values are in the unit of mcd/m^2/lux.
Slope values are in the unit of mcd/m^2/lux per day
Shadowed cells are used as an example in the description

Table 8.2. Yellow Center Pavement Marking R_L Data

	First Round		Second Round		Third Round		Fourth Round		LMEM Model	
No.	Age (Days)	R_L	Age (Days)	R_L	Age (Days)	R_L	Age (Days)	R_L	Intercept	Slope
1	51	94	238	91	436	91	596	75	99	-0.034
2	51	114	237	102	435	102	599	83	117	-0.051
3	86	128	273	118	471	*	635	*	134	-0.061
4	87	158	273	124	471	#	635	69	166	-0.145
5	70	132	253	95	448	87	613	68	131	-0.102
6	71	161	253	149	448	128	613	130	164	-0.066
7	69	96	249	89	442	92	607	78	100	-0.032
8	69	89	249	99	442	94	607	77	99	-0.027
9	71	95	245	85	438	90	603	66	100	-0.046
10	63	70	245	69	438	66	602	52	76	-0.033
11	63	103	245	98	440	119	605	107	105	0.006
12	70	181	243	96	439	*	603	*	170	-0.192
13	52	216	224	194	419	176	582	155	220	-0.110
14	51	167	224	149	419	157	584	136	169	-0.053
15	49	126	229	94	428	92	591	80	122	-0.074
16	45	119	225	95	424	82	587	65	119	-0.089
17	52	122	217	117	417	136	579	123	124	-0.0003
18	52	178	217	172	416	167	575	169	180	-0.031
19	58	207	223	190	423	201	585	156	214	-0.081
20	73	144	227	113	425	110	592	100	141	-0.074
21	72	137	226	126	424	121	591	117	139	-0.043
22	72	201	226	184	424	178	591	150	207	-0.091
23	70	166	224	157	422	138	589	120	174	-0.088
24	35	179	190	140	388	123	555	114	172	-0.112
25	49	132	204	126	402	96	560	83	139	-0.096
Mean	**62**	**141**	**234**	**123**	**431**	**120**	**227**	**103**	**143**	**-0.069**

* Data are missing due to pavement resurfacing and marking restriping.
\# Circumstances prevented the collection of these data.
R_L and Intercept values are in the unit of mcd/m^2/lux.
Slope values are in the unit of mcd/m^2/lux per day
Shadowed cell is used as an example in the description

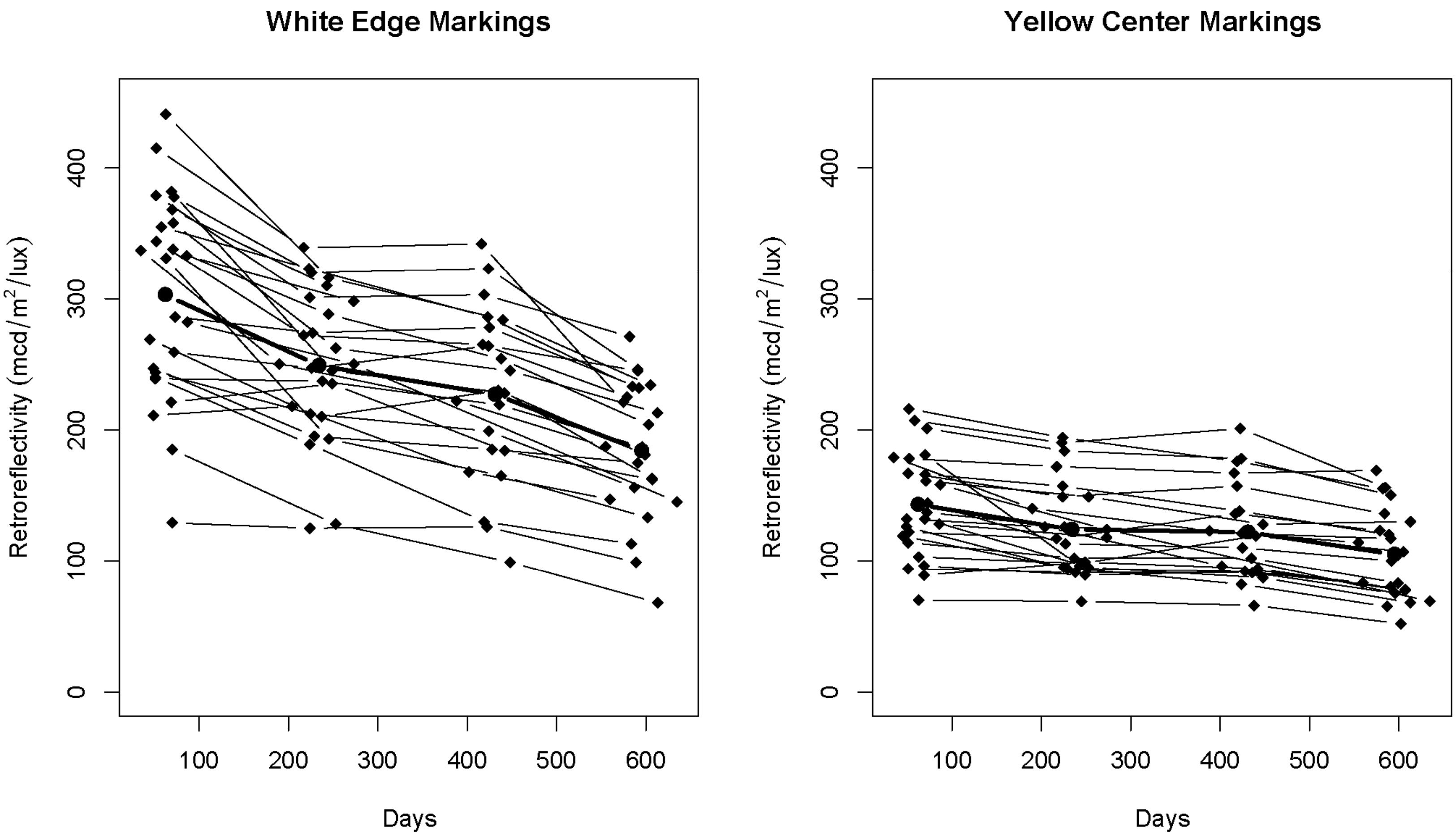


Figure 8.1. Paint Pavement Marking Retroreflectivity Plots

Figure 8.1 indicates that each sample marking has its own trajectory. The performances of each marking are quite different from each other. Figure 8.3 shows the retroreflectivity performances of two specific roads (roads 11 and 23 from Figure 8.1) and the population average of the 25 roads. The retroreflectivity measurements on road 11 are consistently higher than the population average. The measurements on road 23 are consistently lower than the average. The R_L measurements on road 11 are more than double the measurements on road 23.

The marking performance differences are due to several reasons. First, we found that the bead densities of the markings were in a wide range [Zhang et. al. 2009]. Second, the markings were installed by four different crews using different paint trucks. The paint thicknesses were believed to be different. Third, the pavement surface type may have an impact on the marking retroreflectivity. Generally speaking, markings on plant mixed pavement have higher retroreflectivity measurements than markings on bituminous surface treatment (chip sealed) pavement. Other factors mentioned in the Introduction Section may also have impacts on the markings performances.

Figure 8.1 also indicates that the measurements of white edge markings are obviously different from yellow center markings. The range of white edge marking measurements was 80-430 mcd/m^2/lux. The range of yellow center markings was 70-220 mcd/m^2/lux. Thus, it is clear that the yellow markings were significantly less reflective than white markings. The two bold lines in the Figure 8.1 show the average marking retroreflectivity values on the 25 roads over time. The average measurements of white edge markings were 303, 249, 227, and 184 mcd/m^2/lux for the four rounds (decreasing over 2 years) of measurements, while the average measurements of yellow centerline markings were 141, 123, 120, and 103 mcd/m^2/lux. The average degradation rate of white edge markings was -0.225 mcd/m^2/lux per day which was much faster than the average degradation rate of -0.072 mcd/m^2/lux per day of yellow centerline markings.

8.4.4 Marking Retroreflectivity Data Characteristic

Figure 8.1 shows, as expected, that each pavement marking on a specific road has its own trajectory of retroreflectivity as a function of time. For each road, the trajectory looks roughly like a straight line. Therefore, in this study, we assume that retroreflectivity values of particular paint pavement markings degrade in a linear form. Reader should note that nonlinear models can also be used to fit longitudinal data as was previously discussed.

To assess paint retroreflectivity data, we used i ($i = 1,\ldots,m$) as the subscript indexing different roads (units) and j ($j = 1,\ldots,n$) as the subscript indexing measurements in time order within each road (unit). The character m denotes the total number of roads and n denotes the total rounds of data collections. Y_{ij} is a random variable representing all R_L measurements on road i at time t_j [Davidian 2005]. y_{ij} is used to represent an individual R_L measurement.

The natural estimator for the mean μ_j ($j = 1,\ldots,n$) at the jth time point t_j is the sample mean [Davidian 2005]:

$$\bar{y}_j = m^{-1}\sum_{i=1}^{m} y_{ij}$$

For example, $\bar{y} = (303, 249, 227, 184)$ for white edge new markings. The natural estimator for $\sigma_j^{\,2}$ is the sample variance at time j:

$$S_j^{\,2} = (m-1)^{-1}\sum_{i=1}^{m}(y_{ij} - \bar{y}_{\cdot j})^2$$

For each pair of times t_j and t_k, if we graph the observed data values (y_{ij}, y_{ik}) for all $i = 1,\ldots,m$ roads (units), the observed pattern might be suggestive of the nature of the association among responses at times t_j and t_k. However, since the means μ_j and μ_k and variances $\sigma_j^{\,2}$ and σ_k^2 are not the same, it would be better to plot the centered and scaled version of these pairs [Davidian 2005]:

$$(\frac{y_{ij} - \mu_j}{\sigma_j}, \frac{y_{ik} - \mu_k}{\sigma_k})$$

Because we do not know the μ_j or σ_j, a natural strategy is to replace these by estimates and plot the pairs:

$$(\frac{y_{ij} - \bar{y}_{\cdot j}}{S_j}, \frac{y_{ik} - \bar{y}_{\cdot k}}{S_k})$$

Such a graphical display of the observed data is known as a scatterplot matrix [Davidian 2005]. Figure 8.2 shows the scatterplot matrix for the white edge new markings in our sample. The scatterplot matrix for yellow center new markings shows a similar pattern as in Figure 8.2. The subplot in the first row, second column shows the standardized data from the first round (y-axis) and data from the second round of data collection (x-axis). The subplot in the first row, third column shows the standardized data from the first round of data collection (y-axis) and the data from the third round of data collection (x-axis), and so on. The trend for all plots in Figure 8.2 is from lower left to upper right, which means large centered and scaled measurements at one time correspond to large ones at another time. The plots, therefore, indicate that the correlation is strong and positive for each pair of measurements.

The scatterplot matrix shows that R_L measurements on the same marking are positively correlated. The correlation is positive and significant. However, a linear regression model assumes that R_L data collected at different time intervals on the same pavement marking are independent of each other and the correlation to be zero. The linear mixed effects model, on the other hand, can take this correlation into account. Thus, a linear mixed effects model could produce more accurate predictions than a linear regression model with data such as those collected in this study.

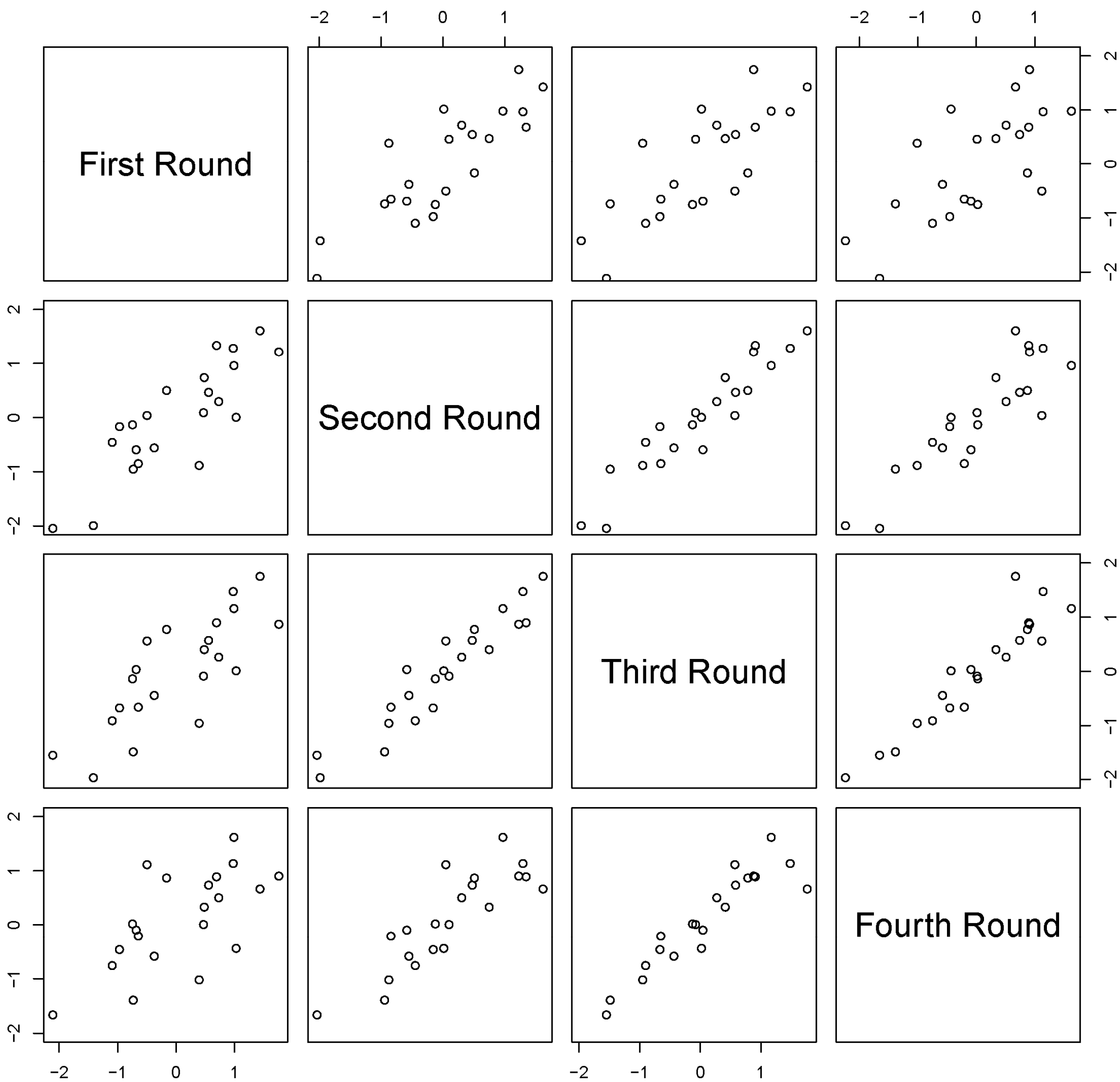


Figure 8.2. Scatterplot Matrix for White Edge Markings

8.5 Methodology

In the following discussion, LMEMs are established based on the paint retroreflectivity data described above. Then, we compare model prediction accuracy between LMEMs and linear regression models. We also show how to use the models at the end of this section.

8.5.1 Linear Mixed Effects Model

We present the development of the linear mixed effects model (it is developed in two stages) in the following paragraphs. We begin the analysis by considering that markings on each road have their own underlying straight line inherent trend. The intercept and slope for a specific road are β_{0i} and β_{1i} ($i = 1, 2, \ldots, m$), which determine the linear trend.

The first stage is at the individual road level. We write a model for the random variables $Y_{i1}, Y_{i2}, \ldots Y_{in_i}$ for the i th road (unit) taken at the time points $t_{i1}, t_{i2}, \ldots t_{in_i}$. The model for road (or unit) i ($i = 1, 2, \ldots, m$) is:

$$Y_{ij} = \beta_{0i} + \beta_{1i} t_{ij} + e_{ij}, \quad j = 1, 2, \ldots, n_i \tag{1}$$

Where:

Y_{ij}	= Response variable
β_{0i}, β_{1i}	= Intercept and slope for a specific road (unit)
e_{ij}	= Random error
i	= The subscript indexing units, $i = 1, \ldots, m$ (m denotes total number of units)
j	= The subscript indexing responses in time order within units $j = 1, \ldots, n_i$
n_i	= Total rounds of data collected for road (unit) i

If we write the parameters in a matrix form, let:

$$\beta_i = \begin{pmatrix} \beta_{01} \\ \beta_{1i} \end{pmatrix}, \; Z_i = \begin{pmatrix} 1 & t_{i1} \\ 1 & t_{i2} \\ \vdots & \vdots \\ 1 & t_{in_i} \end{pmatrix}, \; Y_i = \begin{pmatrix} Y_{i1} \\ Y_{i2} \\ \vdots \\ Y_{in_i} \end{pmatrix}, \; e_{ij} = \begin{pmatrix} e_{i1} \\ e_{i2} \\ \vdots \\ e_{in_i} \end{pmatrix}$$

The model can be expressed as follows:

$$Y_i = Z_i \beta_i + e_i, \; i = 1, \ldots, m, \; e_i \sim N_{n_i}(0, R_i) \tag{2}$$

The factor e_i in equation 2 represents the variation within an individual road (unit); R_i is the covariance matrix.

The second stage is at the population level. Let β_0 and β_1 represent the mean values of the intercept and slope. We define β as the mean vector of the population of all β_i. Then we can write:

$$\beta_{0i} = \beta_0 + b_{0i}, \; \beta_{1i} = \beta_1 + b_{1i}$$

Where b_{0i} and b_{1i} are random effects describing how the intercept and slope for the i th road (unit) deviate from the mean values. Then, we can write the above two equations in a matrix form:

$$\beta_i = \beta + b_i, \; \beta = \begin{pmatrix} \beta_0 \\ \beta_1 \end{pmatrix}, b_i = \begin{pmatrix} b_{0i} \\ b_{1i} \end{pmatrix} \tag{3}$$

We use matrix A_i to represent information such as group membership, allowing the mean of β_i to be different for different groups, so equation 3 can be rewritten as:

$$\beta_i = A_i \beta + b_i, \; b_i \sim N_k(0, D)$$

In this expression b_i represents the variation among roads (units) with a covariance matrix D.

When two parts of the model are combined into a single representation, letting $X_i = Z_i A_i$, the linear effects model is:

$$Y_i = Z_i(A_i \beta + b_i) + e_i = (Z_i A_i)\beta + Z_i b_i + e_i = X_i \beta + Z_i b_i + e_i \tag{4}$$

The coefficient β in equation 4 can be estimated using a maximum likelihood method. The generalized least squares estimator for β is:

$$\hat{\beta} = \left(\sum_{i=1}^{m} X_i' \hat{\Sigma}_i^{-1} X_i \right)^{-1} \sum_{i=1}^{m} X_i' \hat{\Sigma}_i^{-1} Y_i \tag{5}$$

$\hat{\Sigma}_i$ is the estimator of Σ_i and the covariance of Y_i (Σ_i) is:

$$\Sigma_i = Z_i D Z_i' + R_i$$

The best linear unbiased predictor for b_i is:

$$\hat{b}_i = \hat{D} Z_i' \hat{\Sigma}_i^{-1} (Y_i - X_i \hat{\beta}) \tag{6}$$

When an LMEM is used to model pavement marking retroreflectivity data, the β in equation 3 represents the fixed effects and the b_i represent the random effects. We use two variables ($fintercept$ and $fslope$) to represent the fixed intercept and fixed slope, which are characteristics of the population. We also use $rintercept_i$ and $rslope_i$ to represent the random intercepts and random slopes, which are unique to each marking on a specific road. The β and b_i in equation 3 can be expressed as:

$$\beta = \begin{pmatrix} fintercept \\ fslope \end{pmatrix}, \; b_i = \begin{pmatrix} rintercpet_i \\ rslope_i \end{pmatrix} \tag{7}$$

Then, the linear mixed effects model (4) can be expressed as:

$$R_L = (fintercept + rintercept_i) + (fslope + rslope_i) \times Days \tag{8}$$

The coefficients β and b_i in equation 7 (*fintercept, fslope, rintercept*$_i$, and *rslope*$_i$ in equation 8) can be estimated by equations 5 and 6 using SAS statistical software [Davidian 2005]. The *fintercept* and *fslope* coefficients in equation 8 represent the average marking performance, which are same for all markings. The *rintercept*$_i$ and *rslope*$_i$ (i=1, 2, …, 25 for the data collected in this study) coefficients reflect individual marking performance, which are different for each marking. Thus, each road has its own model. For example, the linear mixed effects model for road 11 can be expressed as:

$$R_L = (fintercept + rintercept_{11}) + (fslope + rslope_{11}) \times Days \tag{9}$$

Where:

R_L = Retroreflectivity in mcd/m^2/lux

Days = Days since installation

The estimated coefficients (*fintercept*, *rintercept*$_{11}$, *fslope*, and *rslope*$_{11}$) for road 11 are reported in the LMEM Results Section.

The white edge and yellow center paint marking retroreflectivity data are modeled separately. The data reported in Tables 8.1 and 8.2 were organized into a format that can be imported into SAS. The SAS procedure PROC MIXED was used to model the data [Davidian 2005]. The results of the LMEMs are described in the following section.

8.5.2 LMEM Results

White edge and yellow center paint marking retroreflectivity measurements are significantly different from each other. Thus, their data were modeled separately. The results are also reported separately for white edge and yellow center markings.

For white edge markings, the fixed intercept (*fintercept*) and slope (*fslope*) are estimated to be 310 mcd/m^2/lux and -0.204 mcd/m^2/lux per day (or -75 mcd/m^2/lux per year), respectively. These values represent the average retroreflectivity performance of white edge markings. These values represent the bold line in Figure 8.3.

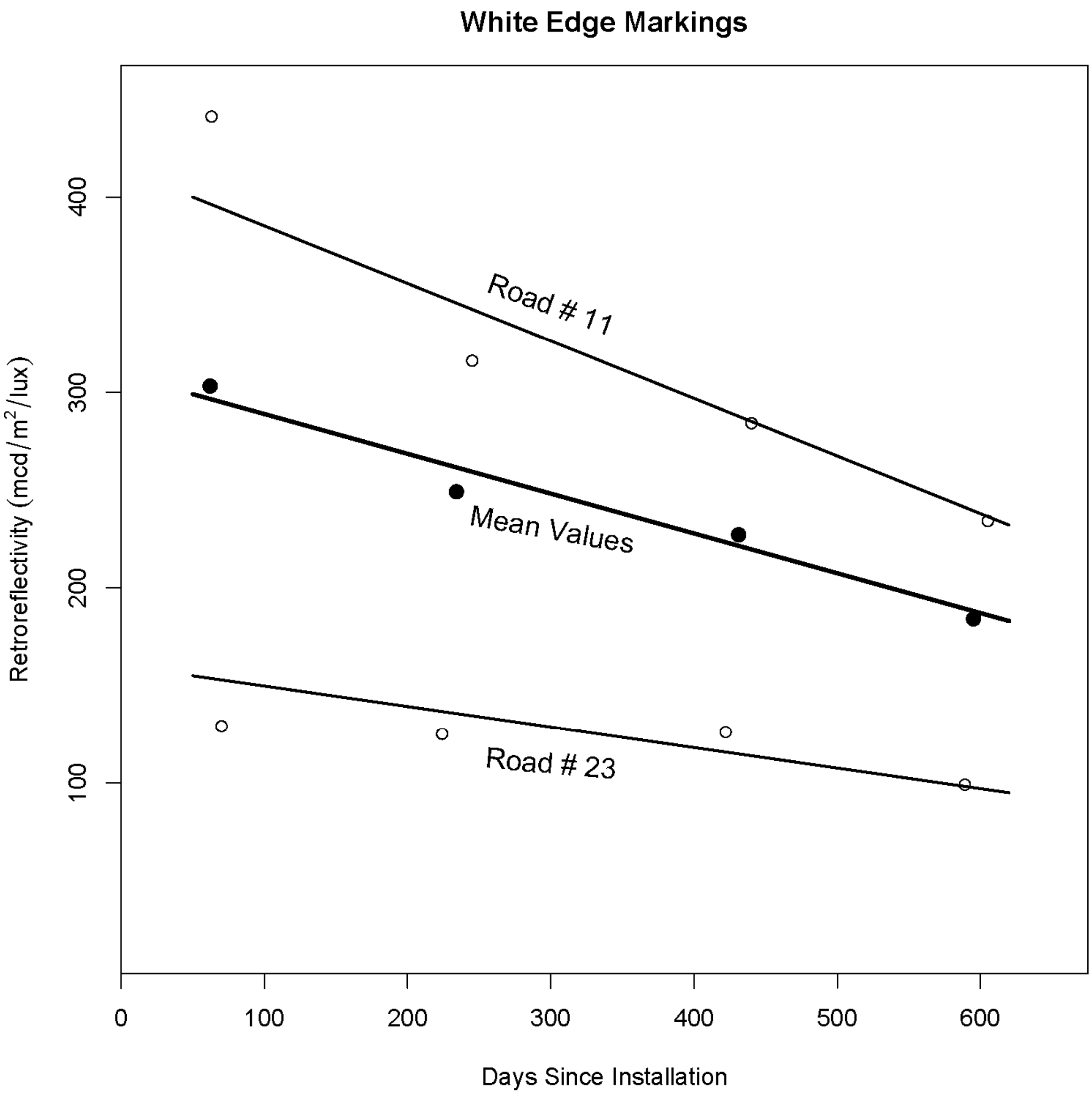


Figure 8.3. Population Average and Subject Specific Retroreflectivity Performance

Columns 10 and 11 of Table 8.1 show the combined intercepts and slopes for white edge markings on each road. The combined intercept is the sum of fixed intercept (*fintercept*) and random intercept ($rintercept_i$) for each road and the combined slope is the sum of fixed slope (*fslope*) and random slope ($rslope_i$) for each road. The combined intercepts are in the range of 161 to 415 mcd/m^2/lux and the combined slopes are in the range -0.105 to -0.295 mcd/m^2/lux per day (-38 to -108 mcd/m^2/lux per year).

Each road has its own combined intercept and slope. For example, the combined intercept and slope for white edge markings on road 11 is 415 mcd/m^2/lux and -0.295 mcd/m^2/lux per day (shadowed cells in Table 8.1). The estimated coefficients *fintercept* and $rintercept_{11}$, are 310 and 105 mcd/m^2/lux, *fslope* and $rslope_{11}$ are -0.204 and -0.091 mcd/m^2/lux per day. The linear mixed effects model for road 11 is:

$$R_L = 415 - 0.295 \times \text{Days}$$

The line is also shown in Figure 8.3.

For yellow center markings, the fixed intercept and fixed slope are 143 mcd/m^2/lux and -0.069 mcd/m^2/lux per day (or -25 mcd/m^2/lux per year), respectively. Columns 10 and 11 in Table 8.2 show the combined intercepts and slopes for each yellow center marking. The combined intercept range is 76 to 214 mcd/m^2/lux. The slope of road 11 (shadowed cell in Table 8.2) is found to be +0.006, which is abnormal and should be a negative value. Other than the abnormal slope, the combined slope range is -0.0003 to -0.145 mcd/m^2/lux per day (-0.1 to -53 mcd/m^2/lux per year).

8.5.3 Prediction Accuracy Comparison

The theoretical analysis in the Marking Retroreflectivity Data Characteristics Section showed that LMEMs should produce more accurate prediction than linear regression models because LMEMs consider the correlation among repeated measurements on the same marking. In this section, we compare the prediction accuracy of the LMEMs and linear regression models (both simple and multivariable linear regression models) using field marking retroreflectivity data.

The first three rounds of retroreflectivity data (data collected in November 2007, May 2008, and November 2008) were used to estimate the coefficients in the LMEMs and linear regression models. The fourth round of data (data collected in May 2009) was used to compare with the predicted values from the models. The fourth round data were not collected on roads 3 and 12 due to marking restriping. Data from these two roads were excluded from the comparison. We used the white edge marking data as an example in the following discussion.

We first use a simple linear regression model to fit the data. The model for a white edge line is:

$$R_L = 309 - 0.206 \times \text{Days} \qquad (R^2 = 0.315)$$

Where:

R_L = Retroreflectivity in mcd/m^2/lux

Days = Days since installation

The predictions of the fourth round of data from the model are shown in the third column of Table 8.3.

In a multiple linear regression model, we use the initial R_L as one of the independent variables [Sitzabee et. al. 2009a]. The model results are similar to simple linear regression model but each road has a different intercept. The multiple linear regression models, with initial R_L as an independent variable, for white edge markings is as follows:

$R_L = 83 + 0.633 \times \text{Initial}R_L - 0.110 \times \text{Days}$ (with an $R^2 = 0.682$)

Where:

$\text{Initial}R_L$ = Initial retroreflectivity measurements in mcd/m²/lux

The fourth column of Table 8.3 shows the predictions for the fourth round from this model.

The intercepts and slopes for each individual road are shown in columns 5 and 6 of Table 8.3. Each marking on a specific road has its own linear mixed effects model. For example, the intercept and slope for road 11 is 406 mcd/m²/lux and -0.268 mcd/m²/lux per day. Then, the model for road 11 is:

$R_L = 406 - 0.268 \times \text{Days}$

The last column of Table 8.3 shows the prediction from the LMEM based on these intercepts and slopes.

Figure 8.4 shows the plots of the residuals for these three types of models (actual measurement minus prediction values). The LMEM prediction plot is more aggregated toward zero than the two linear regression plots, which indicates that the LMEM provides more accurate predictions.

We can use the average squared difference of the residuals as an indicator to compare the three types of models. The average squared difference, SS, is defined as:

$$SS = m^{-1}\sum_{i=1}^{m}(actual_i - prediction_i)^2$$

In this expression m is total number of road sections, which equals 23 in this case. The average squared difference values from simple linear regression, multiple linear regression, and LMEM are 2536, 2066, and 471, which indicated that the LMEM prediction is significantly better than the linear regression prediction. The multiple linear regression prediction was slightly better than the simple linear regression.

The same procedure was applied on the yellow center line new marking data and similar results were obtained. The average squared difference values from simple linear regression, multiple linear regression, and LMEM were 1115, 656, and 137. The results confirmed that the LMEM prediction was better than the linear regression prediction.

Table 8.3. LMEM and Linear Regression Model Prediction Comparison

No.	Actual R_L Measurements	SLR Prediction*	MLR Prediction*	LMEM		
				Intercept	Slope	Prediction
1	187	186	170	273	-0.162	176
2	181	186	173	268	-0.157	174
4	145	178	193	302	-0.193	178
5	68	183	134	192	-0.162	93
6	213	183	243	344	-0.227	205
7	163	184	259	346	-0.245	197
8	162	184	157	259	-0.166	159
9	204	185	232	344	-0.216	214
10	133	185	228	292	-0.231	153
11	234	185	297	406	-0.268	244
13	271	189	260	373	-0.223	243
14	113	189	172	239	-0.188	129
15	175	187	176	255	-0.173	153
16	156	188	190	273	-0.183	165
17	225	190	238	339	-0.212	216
18	221	191	284	409	-0.236	273
19	233	189	245	366	-0.219	238
20	232	187	200	319	-0.178	214
21	245	187	183	295	-0.163	198
22	246	187	258	385	-0.220	254
23	99	188	101	168	-0.119	98
24	187	195	236	315	-0.218	194
25	147	194	156	241	-0.162	150

SLR: Simple Linear Regression.
MLR: Multiple Linear Regression
R_L, Intercept, and Prediction values are in the unit of mcd/m^2/lux.
Slope values are in the unit of mcd/m^2/lux per day

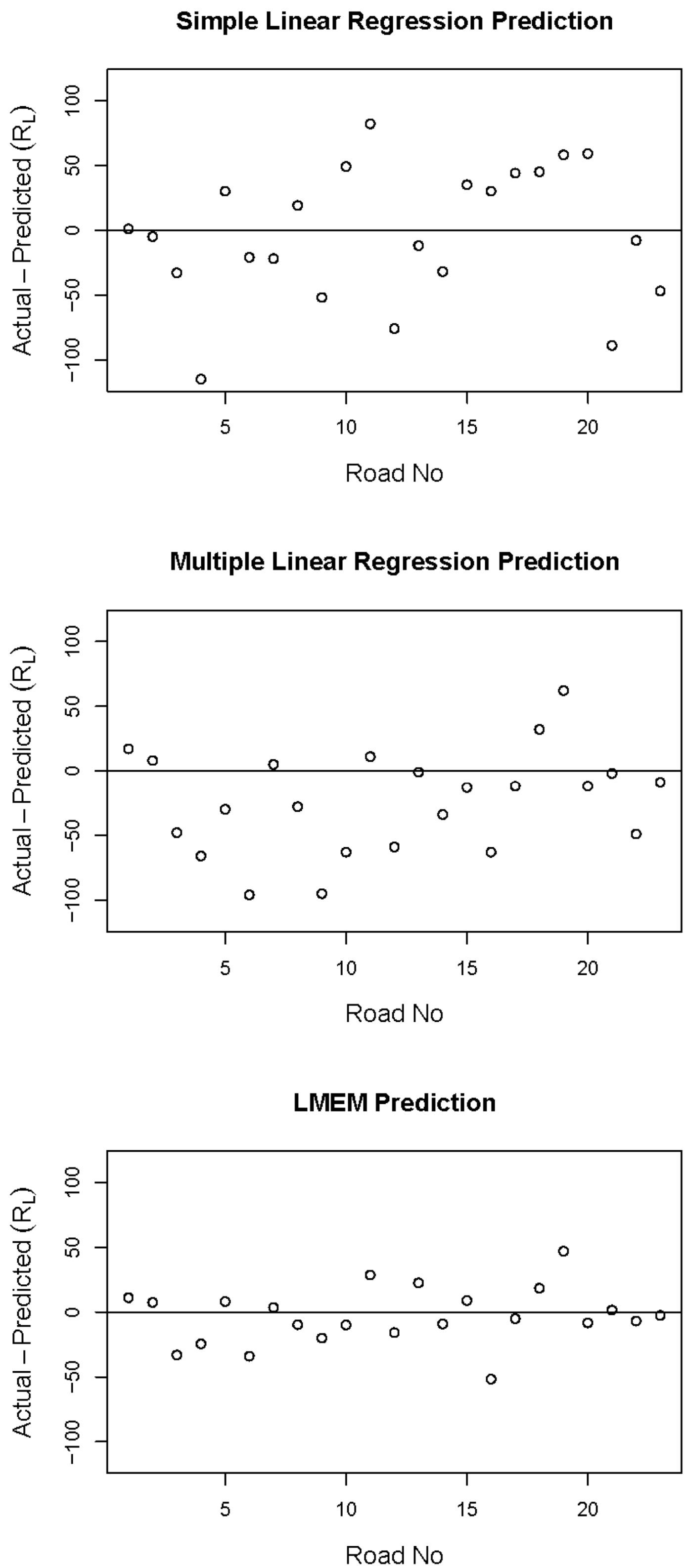


Figure 8.4. Accuracy Comparison of Actual and Predicted R_L

8.5.4 LMEM Application Examples

Agencies can use the LMEM to predict the R_L of a marking when no data are available, when only initial retroreflectivity data are available, or when multiple prior R_L measurements are available for a specific road. In this section we demonstrate how to use LMEM to predict paint marking performance under these varying data availability conditions.

8.5.4.1 Case 1. No Historical Retroreflectivity Data

If a transportation agency does not have any historical retroreflectivity data for a road, the fixed intercept and slope can be used to make a prediction as long as the marking age is known. In this case, the prediction models for white edge and yellow center markings are:

$$R_L = 310 - 0.205 \times \text{Days} \quad \text{(white edge)} \tag{10}$$
$$R_L = 143 - 0.069 \times \text{Days} \quad \text{(yellow center)} \tag{11}$$

These models represent average paint marking retroreflectivity performance over time. If we use 100 and 65 mcd/m^2/lux as the minimum acceptable retroreflectivity values for white and yellow waterborne paints (which are the current effective minima in NC per Sitzabee et. al. (2009a)), and extrapolate the model beyond the range of the database, the estimated the white edge pavement marking life is 1025 days (34.2 months) and the yellow center marking life is 1130 days (37.6 months). However, it should be pointed out that the estimated marking lives represent the average marking performance. It means that almost half of the markings would have R_L values lower than the minima at 34.2 months and at 37.6 months, respectively. Thus, it is clear that restriping at approximately two year intervals is reasonable.

8.5.4.2 Case 2. Initial Retroreflectivity Measurements Available

NCDOT often collects initial retroreflectivity measurements 14-30 days after the installation of a pavement marking for quality assurance purposes. If the initial retroreflectivity measurement data are available for a specific road, in addition to the marking age, the initial R_L can be used as the intercept in the prediction models. The prediction models then become:

$$R_L = \text{Initial}R_L - 0.205 \times \text{Days} \quad \text{(white edge)} \tag{12}$$
$$R_L = \text{Initial}R_L - 0.069 \times \text{Days} \quad \text{(yellow center)} \tag{13}$$

For example, if a white marking has an initial R_L measurement of 250 mcd/m^2/lux, the estimated service life for the marking is 732 days (24.4 months).

8.5.4.3 Case 3. Multiple Retroreflectivity Measurements Available

If multiple retroreflectivity measurements are collected for a specific road (and we know initial R_L and marking age), we could make a more accurate prediction based on all available data (including data collected on other roads). The model was presented in equation 8. The coefficients (*fintercept, fslope, rintercept*$_i$, and *rslope*$_i$) need to be estimated using statistical software.

For example, assume the retroreflectivity measurements on a white edge paint marking are 300, 250, 210, and 170 mcd/m^2/lux at 30, 210, 390, and 570 days. The coefficients in equation 8 can be estimated based on the measurements from this road and all available historical measurements from other roads. The coefficients *fintercept* and *rintercept*$_i$, were estimated to be 309 and -10

$mcd/m^2/lux$ for our sample of 25 roads, for example. The coefficients *fslope* and $rslope_i$ were estimated to be -0.206 and -0.012 $mcd/m^2/lux$ per day. The combined intercept and slope were 299 $mcd/m^2/lux$ and -0.218 $mcd/m^2/lux$ per day for this example. Then, the prediction model for this specific road is

$$R_L = 299 - 0.218 \times \text{Days} \qquad (\text{White edge}, R^2 = 0.315)$$

The estimated service life of this white edge marking is 914 days (30 months).

8.6 Conclusions

LMEMs have three advantages for pavement markings when compared with linear regression models: (1) LMEMs take into account the correlation among repeated measurements on the same marking while linear regression models assume the correlation to be zero; (2) LMEM is flexible and can be applied in different situations; (3) the prediction accuracy of LMEM increases with the amount of historical data available.

Figure 8.2 indicated that the correlation between different rounds of retroreflectivity data was positive and significant. The LMEM considers the correlation while the linear regression models assume the correlation is zero. Thus, the LMEM is more appropriate for pavement marking retroreflectivity data, and likely for other similar data sets, than linear regression models.

LMEM is flexible and can be applied in different situations. In no data are collected on a specific road, prediction equations 10 and 11 are used, which yields results similar to simple linear regression models. If only initial measurement data are available, prediction equations 12 and 13 can be used, which yields results similar to multivariable linear regression models. If more than one measurement is available for the road of interest, the LMEM can use all available data and provide a more accurate prediction than other models.

The prediction accuracy of LMEM increases with the amount of historical data. The estimation of coefficients in equation 8 becomes more accurate if more historical marking retroreflectivity data are available. For a specific road, when more measurements are taken, the performance prediction becomes more accurate.

The LMEM results indicate that paint marking retroreflectivity values vary significantly among different roads. The intercepts and the slopes have wide ranges. To accurately predict the marking performance on a specific road, it is desired to have more than one retroreflectivity measurement taken on the specific road and use LMEMs to predict the marking performance.

The LMEM results indicate that the retroreflectivity performance of white edge and yellow center paint markings is different. The fixed intercept (initial retroreflectivity) of white markings is 310 $mcd/m^2/lux$ comparing to 143 $mcd/m^2/lux$ of yellow markings. The white markings are more than twice as reflective as yellow markings at the initial time. But, the fixed slope (degradation rate) of white markings (-75 $mcd/m^2/lux$ per year) is about three times faster than yellow markings (-25 $mcd/m^2/lux$ per year). This finding is consistent with those of other researchers [Sathyanarayanan et. al. 2008, Sitzabee et. al. 2009a].

The results also indicate that predicted average lifecycles are 34.2 months and 37.6 months for white edge and yellow center markings if we use 100 and 65 mcd/m^2/lux as the minimum acceptable retroreflectivity values, respectively. Thus, the currently NCDOT practice of restriping paint markings at approximately two year intervals is reasonable. However, pavement marking managers should attend to the markings with low initial retroreflectivity measurement (200 mcd/m^2/lux for white edge and 100 mcd/m^2/lux). The retroreflectivity values of those markings are more likely to fall below the minima than other markings in less than two years.

8.7 Recommendations

Pavement marking managers should consider using LMEMs to predict paint marking performance. The prediction accuracy of LMEMs increases with an increased amount of historical data, which makes LMEMs ideal to be used in a pavement marking management system (PMMS) [Sitzabee et. al. 2009b]. When more and more retroreflectivity data are stored in the PMMS, the prediction accuracy of a LMEM increases over time.

This study used field paint marking retroreflectivity data collected in NC. The estimated coefficients of LMEMs are only applicable to the markings in NC. Transportation agencies in other states should collect their own data and establish LMEMs using their own data. However, the modeling method describe in this chapter can also be directly used to establish LMEMs.

This study only collected paint marking retroreflectivity data in the first 600 days after marking installation due to the time constraint of the project funding. The time interval did not cover a full lifecycle of paints. Future research should collect retroreflectivity measurements for a period of time longer than 2.5 years to include data on even older markings.

This study only considered LMEMs for paint pavement markings. It is recommended that similar studies be conducted on other types of pavement marking materials such as thermoplastics, polyurea, and preformed plastics. It would be interesting to know if the retroreflectivity degradation trajectories of other materials perform similarly to paint pavement markings and if the curves are of a linear form.

9.0 DATA INTEGRATION OF PAVEMENT MARKINGS: A CASE IN TRANSPORTATION ASSET MANAGEMENT

There are many components to asset management which include things like asset inventories, condition assessments, and data integration strategies. In many highway agencies separate data managements systems are often incompatible and data integration among these systems becomes impractical or expensive [Gharaibeh et. al. 1999]. Assessing the condition of an asset is labor, equipment, and data intensive and requires the implementation of computing tools. Specifically, the FHWA Office of Asset Management Research and Development Activities highlighted the need for agencies to conduct research on data integration and the various uses of integrated data for asset management [FHWAa, 2007].

Pending FHWA requirements call for assessing the condition of pavement marking retroreflectivity, which means that incorporating computer based automated measurement tools can greatly improve the assessment process. This study provides a solution to the data integration problem of incorporating various attributes of pavement markings, both measured and predicted, into an existing transportation asset management (TAM) system.

9.1 Background

Every asset has a set of attributes and each attribute has a condition at any particular time. One or more measures, typically collected with sensors or other technologies, helps assess the condition. Agencies store these measures as a series of values that represent the asset condition in the form of an asset inventory.

Regulations sometimes establish minimum and maximum allowable values of an attributes condition. In the case of pavement markings the primary attribute of interest to the FHWA is the coefficient of retroreflected luminance (R_L) which is recorded in units of milli-candles per meter squared of luminance ($mcd/m^2/lx$). Of course, there are many other attributes of interest that all need to be considered to effectively and holistically manage this asset. The TAM goal is to find the condition of pavement markings, with regard to their R_L value, and display both the current and future condition in an easy to interpret map format. With good map representations transportation decisions makers can better understand the condition of the asset statewide and take appropriate actions such as better prioritization of the pavement marking budget.

9.1.1 Transportation Asset Management (TAM)

In 2006 Cambridge Systematics, Inc. authored Nation Cooperative Highway Research Program (NCHRP) Report 551, Performance Measures and Targets for Transportation Asset Management. The backbone to this asset management approach is a performance-based framework for decision makers that transcend all levels of the organization [Cambridge Systems Inc., 2006].

NCHRP Report 551 makes a key point of highlighting the need for quality information using scientific methods to collect and analyze data about the asset. Collecting inventory data can be time consuming and costly. Furthermore, the quality of data is one of the most important factors for implementing IT systems [Rasdorf et al., 2003]. The validity of the analysis hinges on the quality of the data used to perform the analysis. Estimating the condition of an asset relies heavily on the five parameters highlighted by Rasdorf et al., which are positional accuracy, attribute accuracy, data lineage, completeness, and consistency [2003].

Previous research has found that mobile collection is the most practical, safe, and efficient method of collecting retroreflectivity data [McDiarmid, 2001]. However, in a large transportation system, mobile collection can still only measure a small percentage of the total asset. For example, NC measures approximately ten percent of the roadways at a cost of approximately $200,000 per year. Statistical methods to estimate the rest of the condition of the asset is a way to generate quality information about the asset while saving nearly $1.8 million dollars per year in data collection alone.

Estimating the condition state of an asset follows the TAM process which according to the Federal Highway Administration (FHWA) is a cost effective approach to systematically measure, maintain, upgrade and operate a physical asset. The process combines engineering principles with sound business practices and economic theory for the purpose of improving decisions regarding the asset [FHWA, 1999]. Pavement is an example of an important transportation asset and pavement management systems are the tools for collecting and monitoring TAM information.

9.1.2 Definition of the Asset

The first and most crucial step to asset management is to clearly define each of the assets in terms that are clear and measurable. There are six parameters that define the pavement marking asset in a measurable way providing a common understanding throughout the organization. At the same time they provide enough detail for effective asset management. For pavement markings these parameters are defined below using a standard format for NC's transportation assets [Love, 2007].

- Asset Identification: Pavement marking.
- Decision Actions: Marking/re-marking. Management is concerned about all the issues associated with marking and remarking pavements. This would include safety, service life, budgeting, and compliance with Federal standards.
- Condition Indicator: The condition indicator defines the basic LOS increment; here, color-coding is used to define the condition of pavement markings while offering the capability to display the LOS cartographically.
- Performance Measure: The performance measure for pavement markings is the coefficient of retroreflectivity luminance (R_L), which is measured in mcd/m^2/lx.
- Performance Target: The performance target is a percent compliance with any established standard for pavement markings. The performance target is the specific and measurable goal to achieve with this asset.
- Minimum Standard: The minimum standard for pavement marking retroreflectance is represented by a LOS "red" in Table 9.1. The standard complies with proposed Federal standards and is clearly measurable.

9.1.3 Level of Service

Translating R_L into level of service (LOS) increments enables agencies to quantify or characterize the condition of the attributes of an asset in a meaningful way for decision makers. LOS is the common definition that provides the foundation to implementing tools that use existing data to predict the condition state of the asset beyond the boundaries of the sample data. That is, we want to appropriately and optimally sample, and then extrapolate what we find to the larger asset population. We do this because many assets are too numerous to individually measure. Additionally, LOS increments allow for a simplified method to assess conformance of an asset's conditions against a set of regulations. Finally, LOS increments can clearly relay information about the condition of an asset to legislators who ultimately control the funding and to the public.

Table 9.1 shows the five LOS increments that were established for pavement markings in NC [Sitzabee, 2008]. The left columns show the increment values for thermoplastics and the right columns show the increment values for paint-based markings. All values are in mcd/m^2/lx. The red LOS indicates the minimum standard for retroreflectivity that will be used by NC until the Federal standard is published. This minimum standard is used to define the end of service life condition.

A graduated LOS scale was used where blue indicates the pavement marking at the highest LOS and red indicates pavement markings that no longer meet the minimum requirements for NC pavement marking retroreflectivity. The following statements qualitatively define the LOS increments:

1. LOS Blue (A): This section of pavement marking is operating at the highest level of service with greater than five years of service life remaining. No action is necessary.
2. LOS Green (B): This section of pavement marking is operating sufficiently and is expected to have two to five years of service life remaining. No action is necessary.
3. LOS Yellow (C): This section of pavement marking is nearing the end of its effective service life and likely has one to two years of service life remaining.
4. LOS Amber (D): This section of pavement is within one year of failure and will likely need to be replaced in the next year's restriping schedule.
5. LOS Red (F): This section of pavement marking is below the minimum standard for pavement marking. There is no remaining service life left and this section should be replaced as soon as possible.

9.2 Pavement Marking Transportation Asset Management System

TAM requires the implementation of tools such as software, hardware, databases, and data collection systems. Combining new and old tools, this study addresses the need for better data integration and utilization while incorporating current information technologies. The first step of the "generic process," as presented by the FHWA in 2007, is to inventory the asset and determine its current condition and performance. The second step is to predict the condition and performance of the asset over time. Both steps benefit from and even require the integration of automation, computing, IT, sensors, and controls.

Table 9.1. LOS Increments and NC Minimum Retroreflectivity Standards

LOS	Thermoplastics		Waterborne Paint	
	White	Yellow	White	Yellow
Blue (A)	≥ 275	≥ 210		
Green (B)	200-274	145-209	≥ 250	≥ 215
Yellow (C)	175-199	125-144	150-250	115-215
Amber (D)	150 - 174	100 - 124	100-149	65-114
Red (F)	≤ 149	≤ 99	≤ 99	≤ 65

The TAM system shown in Figure 9.1 illustrates the data integration of pavement marking attributes and predictive models that will provide the best possible prediction of R_L at any given point in time or space. Highlighted by the dashed line are the key components of the system. These components represent the data integration elements of the pavement markings TAM system and are a significant contribution presented in this chapter. Each component within the system is further defined below. Additionally, each component in Figure 9.1 designates the appropriate corresponding table or figure to which it is related.

9.2.1 Pavement Marking Degradation Models (Predictive Models)

Thermoplastic and paint-based pavement markings make up the majority of markings in place throughout the United States [Migletz and Graham, 2002]. Previously, a statistical analysis established degradation rates for both thermoplastic and paint based pavement markings in NC [Sitzabee, 2008].

The use of statistical methods (based on sampling) to estimate the condition of an asset is a key component to providing quality information while minimizing data collection cost [Cambridge Systems Inc., 2006]. The models presented in Table 9.2 are the result of that previous analysis and are a critical component in the TAM system presented in this chapter.

As shown in Figure 9.1, the predictive models feed directly into the algorithm. The models each require the use of three key variables which are time, initial R_L, and AADT. Each is further defined below.

1. Time – is a continuous variable and is the most significant variable affecting degradation of pavement marking retroreflectivity. All pavement-marking studies reviewed included time as the most significant variable affecting retroreflectivity degradation.
2. Initial Retroreflectivity – is a continuous variable measured in mcd/m^2/lx. This variable is the initial value of retroreflectance and is measured within the first 30 days of application of the marking.
3. AADT - Annual average daily traffic is a continuous parameter that measures the volume of traffic on the roadway in vehicles per day.

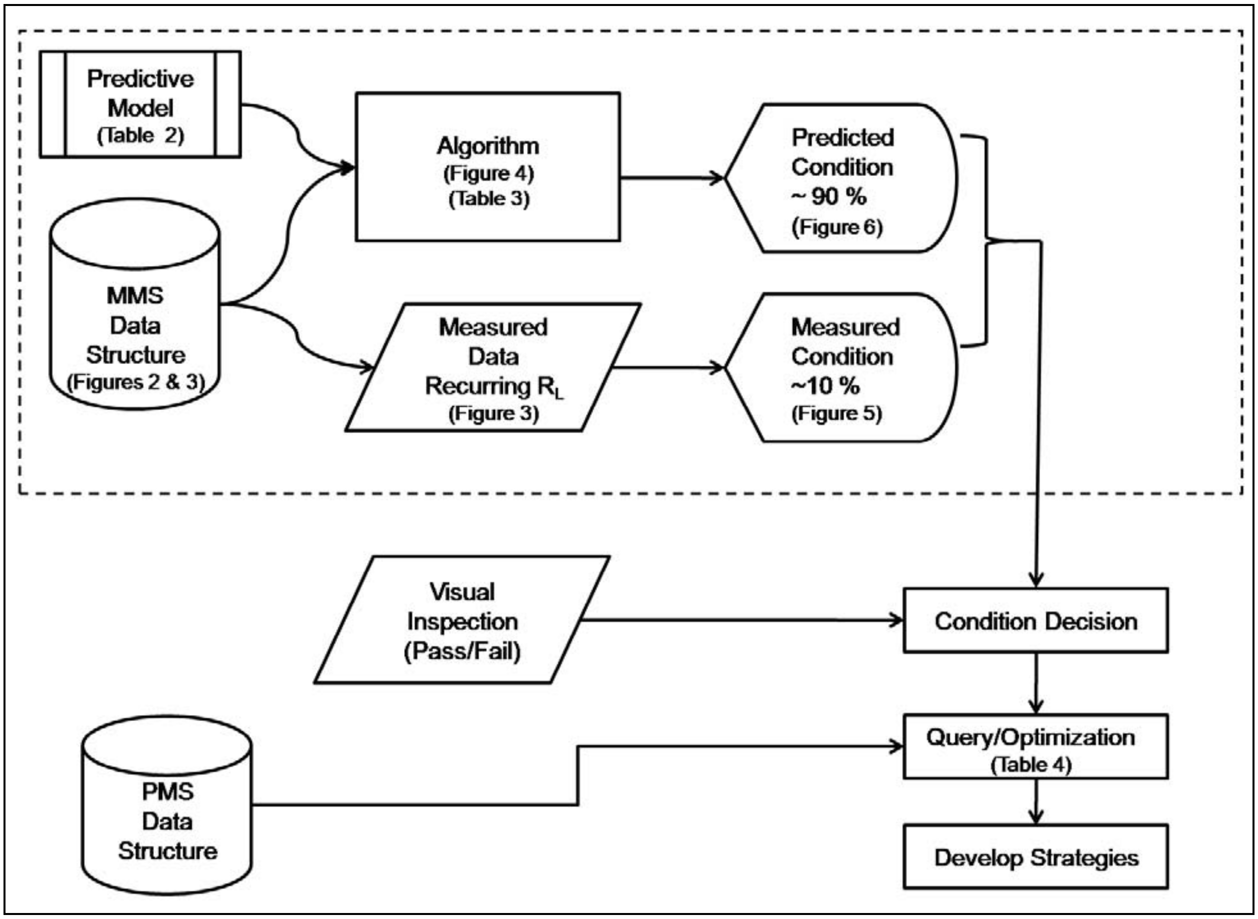


Figure 9.1. Transportation Asset Management System

Table 9.2. Summary of Retroreflectivity Degradation Models

Category	Model
White Edge Thermoplastic	$R_L = 223 + 0.39*R_{L\ Initial} – 2.09*Time – 0.0010*AADT$
White Middle Thermoplastic	$R_L = 173 + 0.59*R_{L\ Initial} – 2.89*Time – 0.0026*AADT$
Yellow Edge Thermoplastic	$R_L = 193 + 0.40*R_{L\ Initial} – 1.69*Time - 0.0016*AADT$
Yellow Middle Thermoplastic	$R_L = 128 + 0.41*R_{L\ Initial} – 1.99*Time$
Paint	$R_L = 55.2 + 0.77*R_{L\ Initial} – 4.17*Time$

Where:

R_L = Retroreflectivity in mcd/m^2/lx
$R_{L\ Initial}$ = Initial Retroreflectivity in mcd/m^2/lx
Time = Time in months since installation
AADT = Annual Average Daily Traffic in vehicles per day

9.2.2 MMS Data Structure

A data model is a set of constructs for representing objects and processes in a digital form [Longley et. al. 2005]. Decisions about the type of data model to use are strongly influenced by types of analysis expected and the level of information available or needed to fully understand the complexity of the system modeled [Longley et al., 2005]. We have chosen to use a relational data model.

There are four major phases to developing a working model of a physical system [Longley et al., 2005]. The first phase consists of developing an understanding of the system and the major components that influence it. Second is the development of a conceptual model, which is a human-oriented (often partially structured) model of selected objects and processes that are thought relevant to the particular problem domain. Third is the development of a logical model, an implementation-oriented representation of reality that is often expressed in the form of diagrams. Finally, the physical model portrays the actual computer implementation using tools such as a relational database or a GIS and often comprises tables stored as files.

9.2.2.1 Physical Model

Development of the physical model is the final step in developing the data management system before actual implementation. In the physical model all the necessary components are identified as well as the specific tables needed in each component. Furthermore, key relationships between databases and components are also defined.

The data schema was developed in detail using Enterprise Architect software. The purpose of using data modeling software is to design and build the architecture of a database. Enterprise Architect software has the capability to export a data schema into a variety of database formats compatable with Oracle, Microsoft Access, and SQL databases.

The basic output file generated from the pavement marking (PMS) data structure is an extensible markup language (XML) file. XML files are expected to become widely accepted and a new interface standard [Halfawy and Froese, 2007]. The advantage of using an XML file is the ease with which the data structure can be shared among various information systems. Another distinct advantage of software-generated XML files is the ability to predetermine and specify the type of database system that the XML file will be imported into. Proprietary systems, on the other hand, can often inhibit the ease of integration across an organization [Pradhan et. al. 2007].

To ensure that the data schema could be implemented an XML file was generated for a Microsoft Access database. Once generated, the data schema was exported as an XML file. The XML file was then successfully imported into a Microsoft Access database. Once imported into Microsoft Access a set of sample data was imported to verify that the table structure was complete and that the correct relationships were in place.

When structuring tables for a database model it is important to normalize the structure. This means that one needs to eliminate redundant data and ensure that data dependencies make sense. Eliminating redundant data can be achieved by establishing the appropriate cardinality in the relationship between tables. Grouping data into functional areas which make sense in the domain of interest is also required. In our case this was achieved by dividing the database tables using a temporal theme. The initial marking table contains all the static characteristics of pavement markings. Each additional table maintains only the attribute values that would change over time.

Figure 9.2 shows the physical model. The model elements are:

1. The core module which stores the non-spatial data about the road network. This is maintained as tabular data in a relational database.
2. The road-line-work data which stores the spatial model of the road system. It is structured as an ARCGIS personal geo-database (which is similar to a Microsoft Access database) that includes all the topological and geometric relationships of the network.
3. The cost and budget element which is a tabular database that contains the maintenance and repair cost data. These data are maintained in a separate database than that of the roadway data (core module).
4. The maintenance element contains all the maintenance and repair data. This is also known as the Maintenance Management System (MMS). This module contains all the non-spatial maintenance and repair information maintained by the agency. This database also contains all the condition assessment information collected from the maintenance condition assessment program which is a biennial condition assessment based on a random sample process.
5. The pavement marking relational database whose schema is defined in Figure 9.3. It contains all of the necessary attributes for pavement marking management.

9.2.2.2 Database Organization of Pavement Marking Attributes

This section presents the organization of some of the pavement marking attributes in a relational database format that follows the structure of the NCDOT core module [Smith, Tran, and Rasdorf, 2001]. This formatting is crucial since it will enable the linkage of pavement marking data with the myriad of data already available throughout the NCDOT.

The tables are presented below using a common format [Smith et. al., 2001] where the table name is presented along with its primary key and attributes. The primary key is the unique value that identifies each row in the database table. The table name is bold and the primary key is bold and underlined.

9.2.2.3 Proposed Tables for Pavement Markings

This section presents the tabular structure of the pavement marking database. The tabular structure presented here provides all the necessary information required to implement the data structure for pavement markings whether one is using the MMS front-end software or any other existing software package.

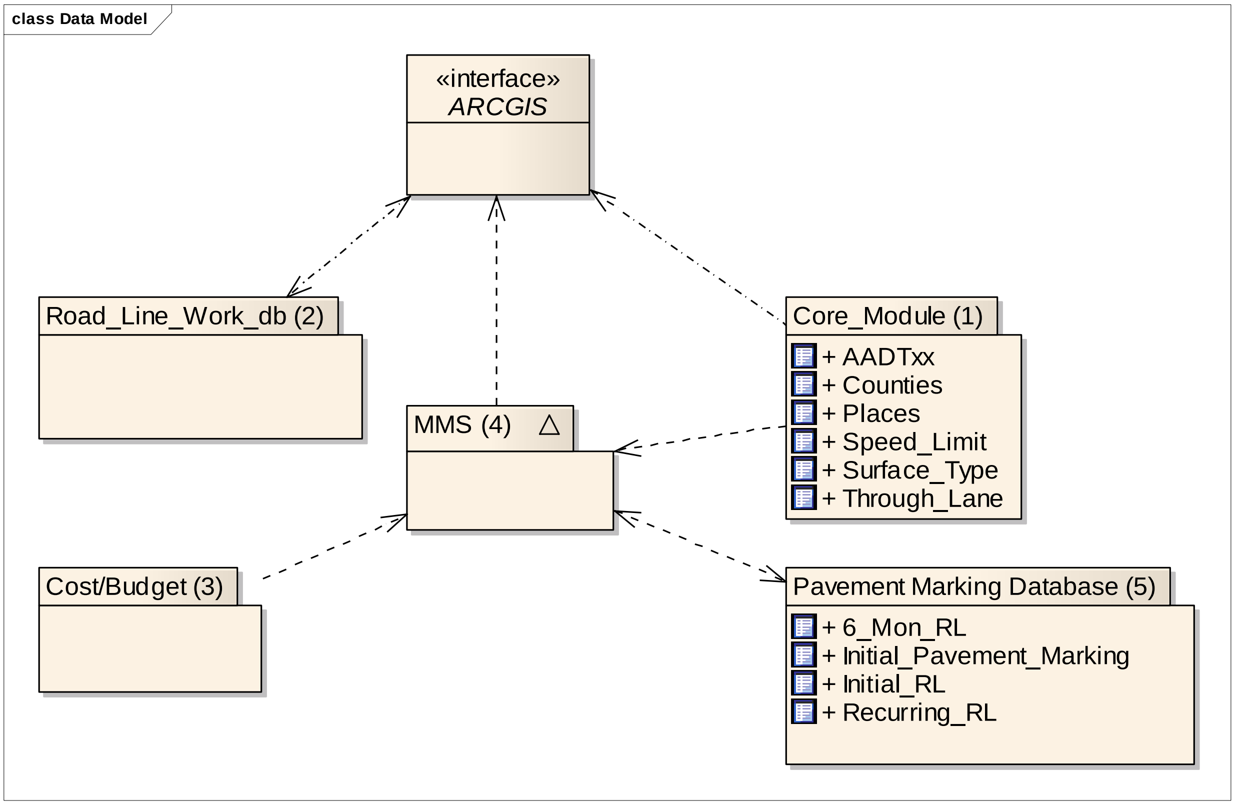


Figure 9.2. Physical Relational Database Management System Model

Initial Pavement Marking (**Place ID**, Color, Material Type, Lateral Location, Thickness, Width, Bead Type, Cost, Manufacturer, Product Name, Installation Temperature, Lineage, Application Date, GPS Coordinates)

The initial pavement marking table contains all the attributes that would be defined at the installation of a new pavement marking.

Place ID – Unique name/label given to the road segment under consideration
Color – White or yellow
Material Type – Paint, thermoplastic, polyurea, epoxy, or other
Lateral Location – Edge or middle
Thickness – Thickness of marking material in mils
Width – Width of marking in inches
Bead Type – Standard, large, or highly reflective elements
Cost – Cost of marking per linear foot
Manufacture – Name of the material manufacture
Product Name – Name of the product used for marking
Installation temperature – Ambient air temperature in degrees Fahrenheit
Length – Length of the pavement marking in miles to the tenth
Application Date – Date of the marking installation
GPS coordinates – Latitude and longitude of the pavement marking initial start point

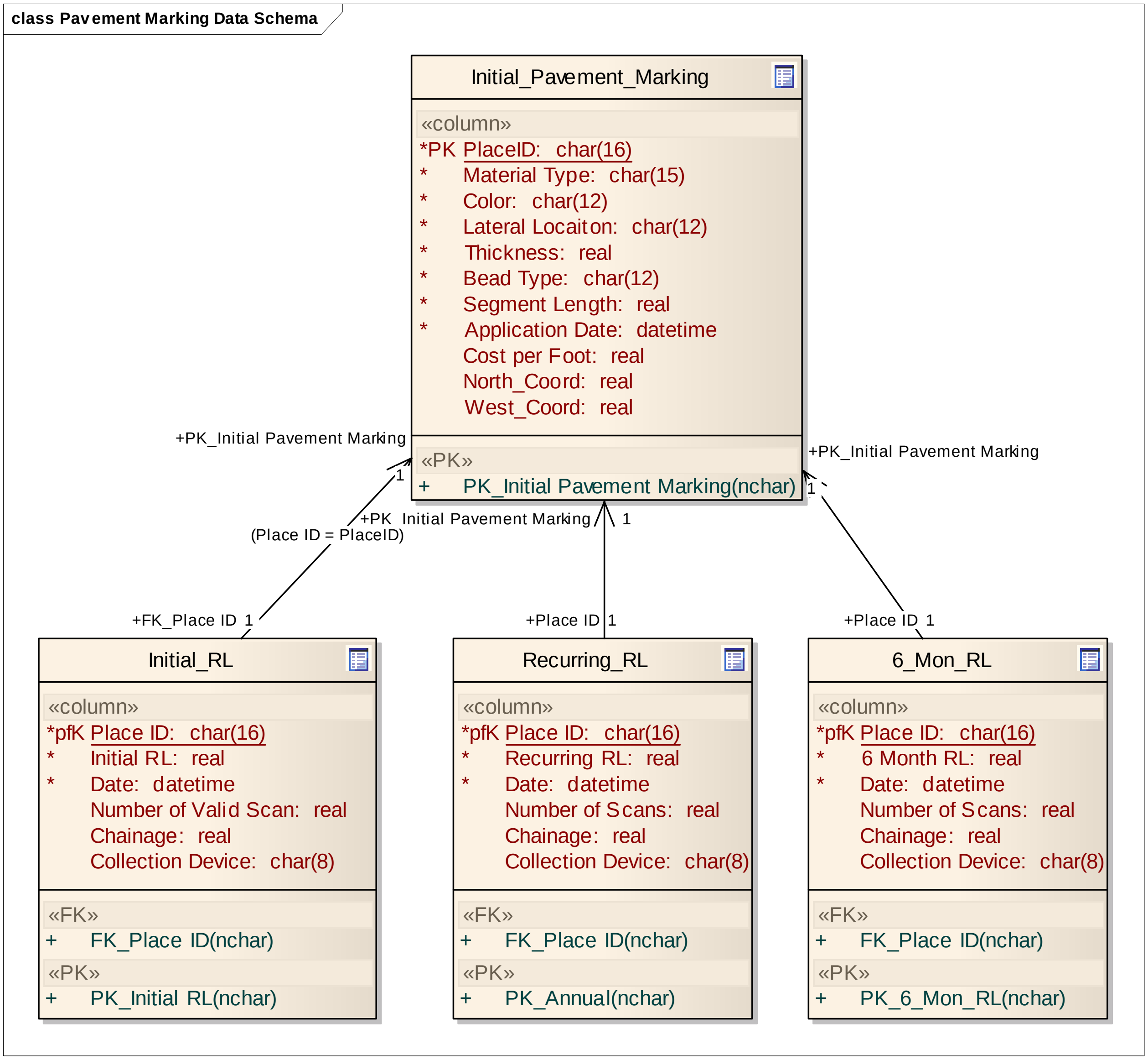


Figure 9.3. Pavement Marking Database Schema

Initial R_L (**<u>Place ID</u>**, Initial R_L, Date, Number of Valid Scans, Chainage, Collection Device)

The initial R_L table defines the initial retroreflectivity characteristics associated with a pavement marking. Although the R_L values could be associated with the Initial Pavement Marking table, initial R_L is typically collected 14 – 30 days after the installation of a pavement marking and warrants management in an independent table.

<u>Place ID</u> – Unique name/label given to the road segment under consideration
Initial R_L – Initial retroreflectivity value in mcd/m^2/lx
Date – Date of the initial R_L data collection
Number of Valid Scans – Records the number of valid R_L values over a tenth mile increment
Chainage – Tenth mile increment for the road segment under consideration. The value always starts at zero from the beginning road segment node and increases in tenth mile increments until the segment run ends.
Collection Device – Laserlux or LTL 2000

Recurring R_L (**Place ID**, Recurring R_L, Date, Number of Valid Scans, Chainage, Collection Device)

Similar to the Initial R_L table, the recurring R_L table defines the retroreflectivity characteristics associated with the pavement marking on a particular date when measured. The attribute fields remain the same as the initial R_L table with the exception of the recurring R_L field. This table could be specifically labeled for specific dates of interest like quarterly, 6-month, or annual R_L.

9.2.3 Algorithm

Consistent with the need to use GIS to solve practical transportation issues [Venigalla and Casey, 2006] this section provides a procedure, in the form of an algorithmic process, to solve a pavement marking management issue. Specifically, this process will display the predicted condition of the unmeasured pavement marking asset at any point in time. For NC this is approximately 90 percent of the asset (the initial 10% is actually measured). Figure 9.4 shows a diagram of the algorithm developed for processing pavement marking retroreflectivity data.

The purpose of the algorithm is to identify all the inputs, processes, and outputs necessary to determine retroreflectivity values and to spatially display them for a given road segment. The algorithm could be used to spatially display retroreflectivity values for any DOT, agency, or organization with a similar database structure.

The algorithm identifies the steps necessary to meet the organization's primary asset management goal, which is to determine the percent compliance with governing regulations for any regulated attribute, in this case for pavement marking retroreflectivity. Here the final output displays the performance-based predicted retroreflectivity values in their current or future state. By displaying the condition in the predetermined LOS identified earlier the user can easily see where the pavement markings fall below the minimum requirements. This can be done in the current condition or by adjusting the date of interest to predict the condition state at some future point.

Table 9.3 presents each process used in the algorithm. Identified for each process are the required inputs and the expected output. Column two shows the procedural steps which correspond to the step numbers identified in the diagram. The time process requires the user to identify a date of interest. This could be set with a default for the current date and would result in displaying the predicted retroreflectivity values (of the 90% of unmeasured roads) in their current state. However, the date could be easily modified to project the condition state at some point in the future (for all roads).

The algorithm shows the display as an end state but this could be further refined to display all the retroreflectivity values sorted by LOS increment. This makes it easy to create a cartographic image identifying the condition of the asset. One possible result is a map of all retroreflective values that are below the minimum standard. By adjusting the LOS increments to match their own standards, any state agency could implement this algorithm and display current or future condition state for retroreflectivity.

9.2.4 Measured Data

In NC approximately 10 percent of the pavement markings retroreflectivity is still measured on an annual basis (this is done to ensure the desired level of quality control). For roadways with such measured data it would be foolish to use predictive models to estimate the retroreflectivity values. In this case the TAM system bypasses the predictive algorithm and goes directly to a display option. Since this data structure uses a relational database the display can be tabular or can be presented graphically through GIS on an easily understood map.

Of course, measured data identifies the value of a condition attribute at one specific point in time. Additionally, managers have the option to display the condition of the measured data at a specific time side-by-side with the predicted condition at the same time, as shown in Figure 9.6 of the example below. This will give managers the ability to adjust the prediction appropriately for the current condition. Since a small portion of the asset's condition is still measured, these measured sections can be used to calibrate or even update the predictive models used in the process.

9.3 Condition Decision to Perform Queries and Develop Strategies

Recall that the goal of a TAM system is to provide managers with the best possible condition of the asset, either predicted or measured. The process presented here implements computing tools and enables managers to make decisions based on a state-wide condition assessment that was previously unavailable. With the inclusion of the visual inspection process the decision maker now has a clear and holistic view of the asset. Although not the primary focus of this study, this section summarizes the use of visual inspections and the integrated use of a pavement management system as shown outside the dashed line in Figure 9.1.

9.3.1 Visual Inspections

There are both objective and subjective evaluation systems in use today to measure retroreflectivity of pavement markings. Objective measurements use retroreflectometers (mobile or handheld) while subjective evaluations are typically done through visual inspections by a trained observer. Both approaches are considered viable methods for measuring retroreflectivity in the United States [Migletz and Graham, 2002], the latter because of cost considerations.

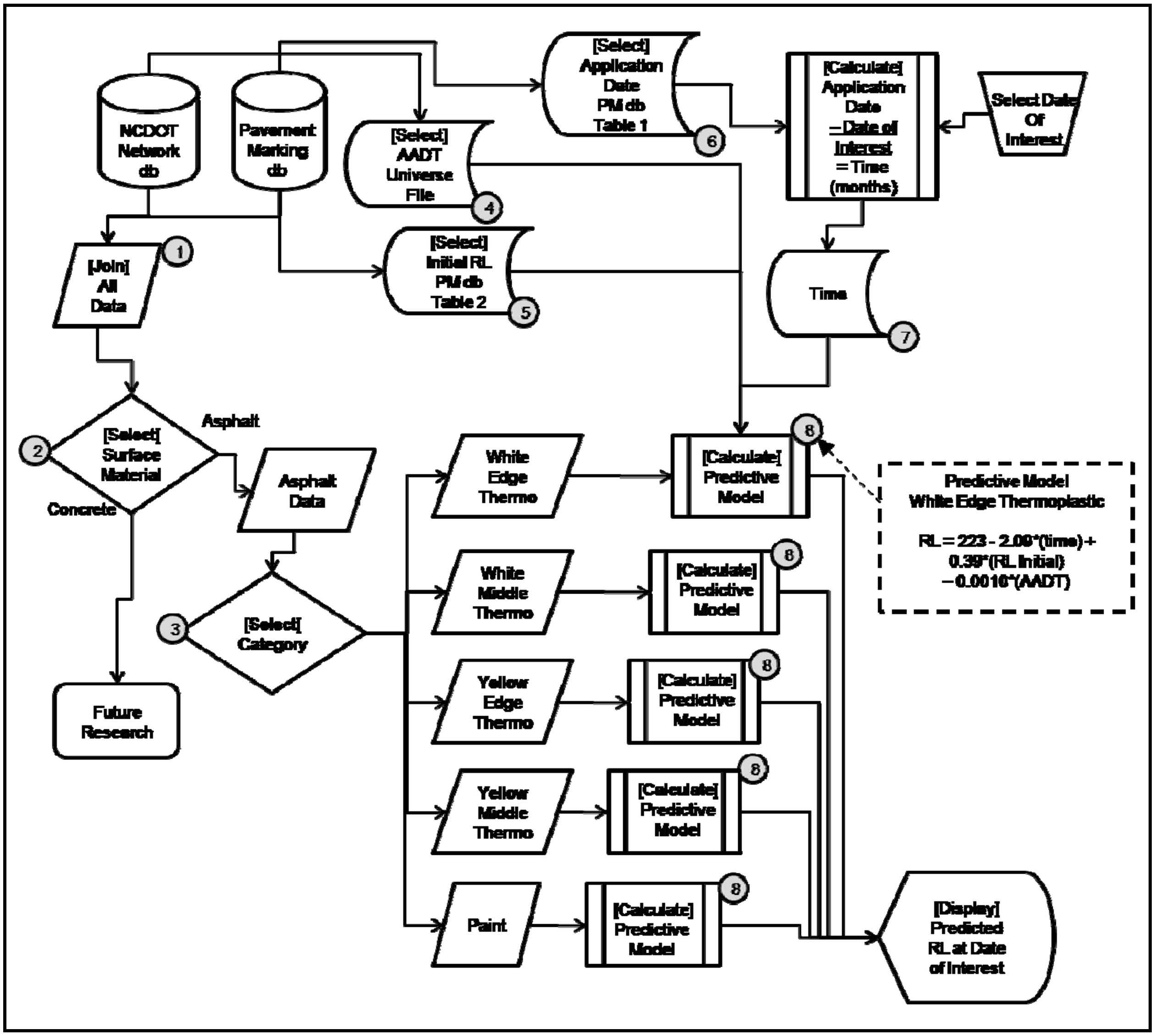


Figure 9.4. Pavement Marking Retroreflectivity Algorithm

Trained observers can typically estimate the condition of the asset and determine whether the asset needs to be replaced or not [Migletz and Graham, 2002] . Incorporating the human factor (inspectors) into the TAM decision loop provides feedback to the process that helps to evaluate the accuracy and viability of the process. Additionally, the system can be used to prioritize the road segments selected for visual inspections. For example, managers might want to visually inspect a section of road that is reporting inconsistent predictions or other roads in areas where the measured values are old and are no longer reliable.

Table 9.3. Process Input and Output for Pavement Marking Algorithm

Process	Step Number	Input	Output
Join all data	1	• Core Module • Road line work • Pavement marking data	All data
Select surface material	2	All data	Asphalt PM data
Select category	3	Asphalt PM data	PM data by category
Select AADT	4	Core Module	AADT for segment of interest
Select initial R_L	5	Pavement marking data	R_L for segment of interest
Select application date	6	Pavement marking data	Application date for segment of interest
*Time process	7	• Application date for segment of interest • *Date of interest	Time in months
**Calculate R_L using predictive model	8	• PM data by Category • Time • initial R_L • AADT	Display R_L at date of interest

* Requires user input

** Use appropriate model for category where Paint only requires time and initial R_L

9.3.2 Pavement Management System

Recall that Figure 9.1 shows a link to an existing pavement management system (PMS). This link provides managers with information to optimize the transportation asset management beyond pavement markings.Using the power of a GIS, a user can integrate information from various sources and spatially connect that information to identify aspects of the transportation system that would otherwise be unapparent [Flintsch et. al., 2004]. Armed with the best possible estimate, the asset manager can use a GIS to perform queries on the system and explore spatial relationships of the asset. This is particularly useful in optimizing project funds and leveraging existing systems in developing strategies for pavement markings.

Inclusion of the PMS is an additional piece to the overall strategy development. Although external to pavement markings the PMS provides managers with the holistic picture of the roadway and enables managers to make smart decisions regarding pavement markings. For example, on a given road segment a pavement marking manager might decide to use a long-life marking but prior to implementation he queries the projected maintenance activities from the PMS to see that the road segment is scheduled for resurfacing the very next year. Now the appropriate decision might be to use a shorter life material (cheaper) thus aligning the pavement marking material life with that of the road surface.

9.4 Limitations

There are two key limitations that need to be overcome in order to implement the proposed TAM process. First, agencies need to implement a protocol to record the necessary variables needed to implement predictive models. Second, agencies need to overcome location referencing issues. This section highlights these limitations and presents recommended solutions.

9.4.1 Recording Key Variables

The predictive models require the use of initial R_L, time, and AADT. AADT and time are critical but in most cases are readily available. However, initial R_L values are often not recorded, especially for in-house performed work. In the case of NC this represents approximately 60 percent of the roadway. The authors advocate that recording the initial R_L value and installation date are easy to do. These values can be measured at the time of installation and then recorded in the MMS when the marking crews record other information such as labor hours.

In the case where initial R_L values are not available and a highway agency didn't want to add the expense of collecting and maintaining initial R_L values they could implement two alternative methods for estimating initial R_L. First, the highway agency can use the average R_L value as measured from empirical data for like materials. Second, they could use the required specification value to estimate the initial R_L value.

9.4.2 Location Referencing

Because of the spatial aspect of the transportation system, location referencing is a key component of data integration. Location referencing systems (LRSs) consist of techniques and procedures for accurately collecting, storing, maintaining, and retrieving location information [Flintsch et al., 2004]. Pavement management systems typically use a location referencing method known as linear referencing. This is particularly useful in transportation networks because of its ability to accurately locate most transportation features, including pavement markings, in a one-dimensional form [Flintsch et al., 2004]. The key to GIS and transportation data integration is to establish an LRS identifier which is simply a unique individual identifier specific to a given segment of roadway [Rasdorf, Janisch, and Tilley, 2002].

Another consideration is that the increased use of GIS technologies and automated data collection equipment has increased the use of GPS-based coordinate referencing as a location referencing method [Flintsch et al., 2004]. This is different from a linear referencing system approach in that it identifies a single point in space. Both methods are applicable in transportation applications.

In a nationwide survey of DOT's, 35 percent of agencies surveyed indicated they used a coordinate-based location referencing system [Flintsch et al., 2004]. An additional 13 percent indicated they used a GPS-based state plane coordinate system [Flintsch et al, 2004]. Most agencies indicated that GPS technology was not the sole LRS used and that linear referencing methods were still used in conjunction with the GPS based LRS [Flintsch et al, 2004]. Location referencing remains the most popular method for linking transportation asset management databases and implementing a single state-wide referencing system is a key component to successfully integrating state transportation agency asset management data [FHWAb, 2007].

Unfortunately, the LRS used to identify the location of the pavement marking retroreflectivity data in NC did not follow any of the standard linear referencing formats. The data were collected using a localized LRS that does not conform to either the state or county milepost system. Furthermore, the NCDOT's contract with the data collection contractor did not prescribe that pavement marking retroreflectivity data be collected using a particular location referencing method. The system used by the contractor was a blended system that used route identification with the start and end points of measured sections identified with a mile post, an intersection, or an offset distance. Because of the unique LRS used, the localized referencing system precluded or at least significantly complicated the integration of pavement marking retroreflectivity data with the existing database structure.

Incompatibilities in location referencing posed problems in developing this data model. The LRS component had to be resolved before the physical model could be implemented. Fortunately, NC has the ability to match location using an LRS filter. However, the filter requires the use of one of four supported referencing systems [NCDOT GIS Unit, 2006]. In this case, 2006 and 2007 pavement marking retroreflectivity data contained longitude and latitude data for each 0.1-mile road segment. This information was used by the filter to locate retroreflectivity data (in a GIS) as a feature. Once the data were implemented as a feature, the data were "snapped" to the existing LRS.

9.5 Demonstration

One of our goals is to provide transportation agencies with a mechanism to confidently assess the condition of pavement markings at a point in space and time without having to physically measure all pavement markings. This section presents an example of the end product from implementing the proposed algorithm (using the proposed data structure and pavement marking degradation models).

Figure 9.5 is a thematic map developed using the ARCGIS application of our asset management system and displays the actual retroreflectivity data for the northbound yellow edge line along a 12-mile stretch of Interstate 95 in NC. This equates to displaying the measured condition state shown in Figure 9.1 which follows the measured data path, bypassing the algorithm. The retroreflectivity data were added using latitude and longitude and then the points were "snapped" to a route feature created from the primary roads data file. The values use a graduated scale based on the previously established LOS increments for NC.

Figure 9.6 shows both the actual and predicted R_L values of the northbound yellow edge line for the portion of the interstate illustrated in Figure 9.5. Having both the predicted and measured values displayed side-by-side gives the agency a sense of the accuracy of the process.

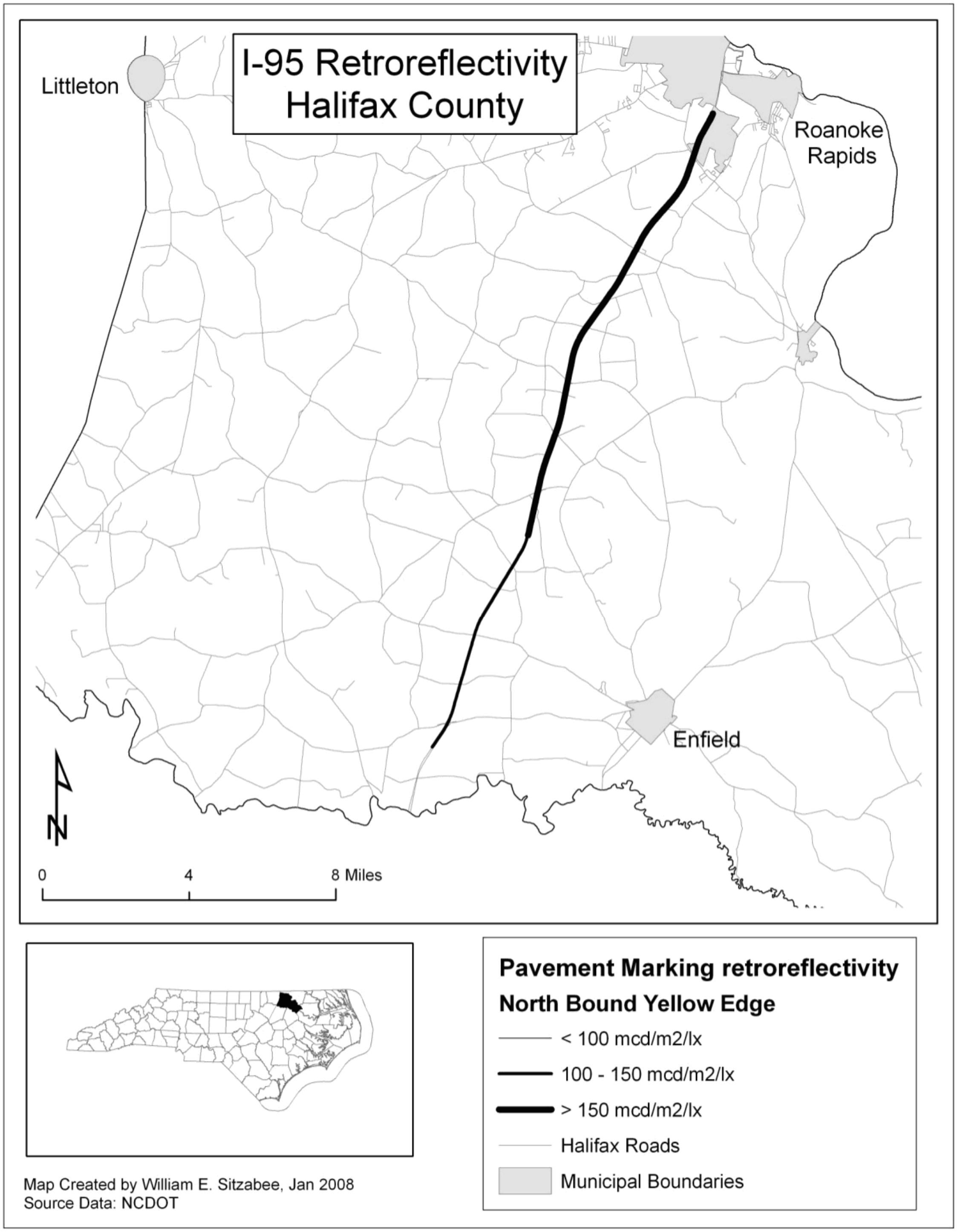


Figure 9.5. I-95 Actual R_L Values for Yellow Edge Pavement Markings

In this case the system achieved a high level of accuracy and was deemed a success. Additionally, the predicted line demonstrates the ability of a transportation agency to estimate the condition of the asset without having to physically measure it. If desired, it is possible to separate and display the measured and predicted data.

Maps like those illustrated in Figures 7.5 and 7.6 provide managers with an effective tool to highlight the condition of pavement markings as an asset. This is useful to convey the condition of the asset to the public and to legislators when competing for funding for this asset. However, thematic maps are not the end products in GIS, but are a means to store information that is necessary for analysis and decision making. Maps, views, reports, and displays can all be extracted from these thematic layers to meet user needs without changing the underlying thematic maps themselves [Rasdorf et al., 2003].

9.5.1 Asset Management Strategies

Table 9.4 is an excerpt from the event table generated in the demonstration and represents another way for managers to use the available data to make asset management decisions. The location column identifies location of a specific road segment (N YE represents a northbound yellow edge line). The predicted R_L value represents the condition state at a specified time of interest, which in this case is October 2007. Also provided in Table 9.4 is the age of the pavement marking when it is expected to reach the minimum standard. This column uses the same predictive model but rearranges the variables to solve for age given R_L equal to the minimum standard value. This enables agencies to determine the year that the marking will need to be replaced, which is the fifth column.

The TAM system allows managers to use updated cost figures, which are constantly changing, by integrating data from external sources, like the PMS. Here the cost per foot column was added to Table 9.4 to demonstrate the ability to combine the cost basis with the condition state and estimate the total cost for that section of road, which is also shown in Table 9.4 (last column). Presenting the data in this way allows managers to determine key budget (as well as maintenance) needs. This is a small example of how queries can be used to influence and help develop pavement marking asset management strategies.

9.5.2 Validation of Models

The TAM system relies on the use of integrated data and predictive models. However, it is imperative that good models be used. To validate the predictive models used on our system we conducted a simulation that matched our demonstration example. Recall that the predicted value for the northbound yellow edge was calculated to be 147 mcd/m^2/lx. This value is determined using the predicted equation which includes the intercept, initial R_L, time, and AADT. The coefficient for each parameter has its own variance.

To further understand the variance associated with a predicted value, a series of simulations was conducted. Summarized in Table 9.5, the simulations used the same input values for the variables as in the single prediction. The difference for the simulation is in the coefficients for each variable as shown in Table 9.5. Here, the coefficients were replaced with a random number generator based on a normal distribution using the mean coefficient value and standard error.

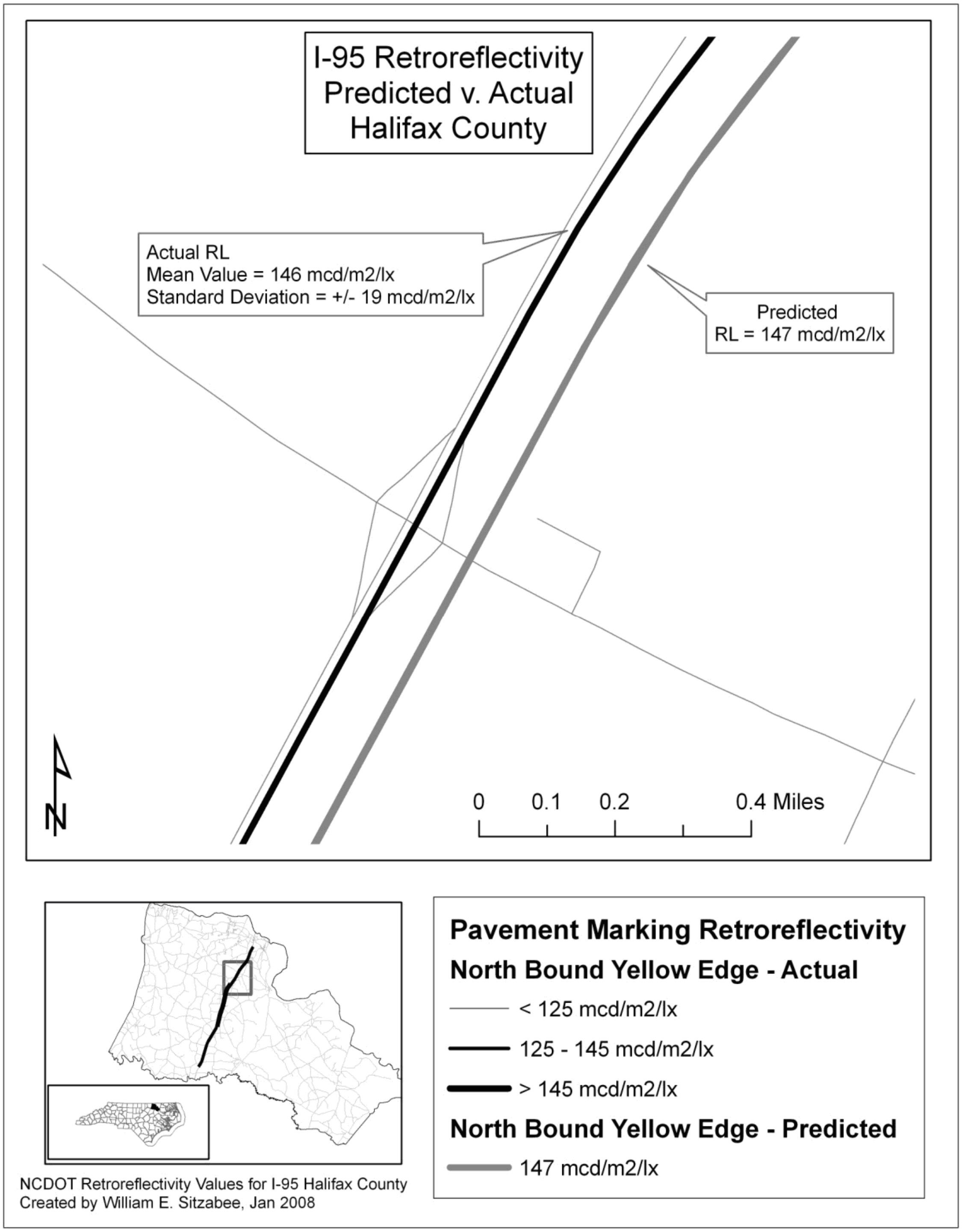


Figure 9.6. I-95 Actual and Predicted R_L Values for Yellow Edge Pavement Markings

The results after 100 simulations, found the average predicted value was 133 mcd/m^2/lx with a standard deviation of 35.9 mcd/m^2/lx. The results of the simulation help us to understand the variance in the predicted value and know that the predicted value can easily differ by as much as 36 mcd/m^2/lx. This is something that managers would need to account for when making decisions.

Table 9.4. Predicted R_L and Cost Data for I-95 Halifax Example

Location	Predicted R_L ($mcd/m^2/lx$) Oct 2007	Age (months) R_L at min	Minimum Standard ($mcd/m^2/lx$)	Replace in FY	Cost per Foot ($)	Total Cost ($)
I-95 N YE	119	78	100	2008	0.55	35,500
I-95 N WE	244	112	150	2011	0.55	35,500
I-95 N WS	149	67	150	2007	0.65	41,900

For example, a predicted value of 147 mcd/ m^2/lx for a yellow edge line would classify the marking as LOS green (see Table 9.1). With a range of 145 mcd/ m^2/lx to 209 mcd/ m^2/lx for yellow thermoplastic markings puts this right on the border of LOS green and yellow. In fact the marking could easily be in the LOS yellow range. Although budget issues and other factors will impact the decision, managers should pay particular attention when markings are within 36 mcd/ m^2/lx of failure. If the measured values were not available this would be a case where managers should consider moving this up on the priority list for a visual inspection.

Table 9.5. Simulator Parameter and Coefficient Estimate Values

Term	Coefficient	Std Error	Variable Input
Intercept	193.3	21.12	-
R_L Initial	0.3963	0.0836	243
Time	-1.69	0.260	60
AADT	-0.0016	0.00044	36500

9.6 Summary

This chapter presents solutions for data integration issues and presents an integrated TAM system for estimating the current and future condition of pavement markings as a transportation asset. This chapter describes the data structure, in the form of a physical model, specifically integrating a pavement marking data schema with existing IT systems (MMS). Software was found to be useful in developing a relational data schema. The software produced an XML file that can be easily imported into a variety of existing database structures.

Additionally, the TAM system included an algorithm that utilizes the data structure to establish the condition of the asset. Using predictive models based on a small sample of measured sections (10 percent), the algorithm estimates the condition of the remaining portion of the asset (90 percent), at any location on the highway system. With the inclusion of measured data and an allowance for visual inspections, managers can query and display the condition of the asset and perform strategy development for maintenance, rehabilitation, or replacement of the asset.

9.7 Findings

Asset management relies heavily on data collection. While much data is collected manually this simply isn't practical. Automated means are critical to effectively support asset management systems. This means that a variety of sensors and data collection devices need to be incorporated into asset management systems. The data also needs to be well organized in integrated databases and be carefully geo-referenced.

Implementing information technology to link predictive models with databases and a GIS, this chapter presented a clear and effectively way to implement an asset management strategy. Relying heavily on IT, the TAM system provided here gives asset managers a way to estimate pavement marking conditions state-wide without having to physically measure the asset. Ultimately, this process eliminates the need to collect data to establish the condition of an asset. With integrated data and smart computing the TAM system shows a method to manage pavement markings without collecting data on every mile of an asset each year. In NC this equates to a $1.8 million annual savings.

Our TAM system includes AADT, time, and initial R_L as critical variables. AADT is readily available to most highway agencies. Installation date directly relates to time and is a must have for predictive models. Both installation date and initial R_L need to be collected (or at least estimated) for use of the predictive models. This study highlights the importance of a highway agency to have good protocols for collecting and maintaining initial R_L data for effective asset management of pavement markings.

9.8 Recommendations

In this chapter, the TAM system was designed for pavement markings but the results from can be generalized to provide a design process for other assets. Furthermore, using the concepts presented herein, system designers can expand the concepts to meet asset management needs for more comprehensive and complex systems.

In many asset management systems there is a need for ongoing data collection. Agencies should implement protocols to analyze data needs. Consideration should be given to the use of automated sensors and smart computing techniques to minimize the amount of data collected and maximize the impact that the data have on managing an asset.

To predict pavement marking condition states requires that initial R_L, AADT, and pavement marking installation data be recorded and maintained in a compatible database similar to the one presented in this chapter. Recording these attributes at the time of installation is highly recommended, would have a nominal cost, and would require little change in current practices. In cases where initial R_L is unavailable or impractical to collect, it is recommended that agencies use empirical data or specification values to estimate the initial R_L.

The inability to locate the attributes of an asset remains the number one issue in implementing effective asset management. LRSs rely heavily on IT and good location referencing is still a significant limitation in managing pavement markings in many DOTs. Because of the spatial aspect of transportation systems it is highly recommended that highway agencies select and implement a single LRS. This will enable agencies to use location as a means of integrating pavement marking data into the overall transportation data management.

Finally, it is recommended that highway agencies continue to use a visual inspection process in their management of pavement markings. The visual inspection can be used to verify the condition estimates produced by the model. In fact, the model estimates can be used to prioritize the visual inspection plan or even prioritize the limited dollars that are available for retroreflectivity data collection. Thus, a dual check and balance is achieved to ensure the best possible estimate for the condition of the asset at any time or location.

10.0 CONCLUSIONS

The conclusions section of the report is divided into three subsections based on the results in previous chapters. These are factors impacting pavement marking retroreflectivity, retroreflectivity degradation models, and pavement marking asset management system.

10.1 Factors Impacting Pavement Marking Retroreflectivity

The impacts of several important factors (such as lateral location, directionality, region, and pavement roughness) on marking retroreflectivity were evaluated in this study. With two large pavement marking retroreflectivity datasets in hand, we evaluated whether these factors have significant impacts on marking retroreflectivity.

The research found that there was a significant difference in the rate of retroreflectivity degradation between edge lines and centerlines for both yellow and white thermoplastic markings. The results indicated that edge lines degraded at a slower rate than center or skip lines for both white and yellow thermoplastics. Both the un-weighted and weighted ANOVA analysis indicated that there is a consistent 85 percent or greater probability that edge lines and center lines degrade at different rates from six months through five years for both yellow and white thermoplastic markings.

Paint pavement marking centerline retroreflectivity values measured in the direction of paint striping were found to be significantly higher than the values measured in the opposite direction. The differences were normally in the range of 20-50 mcd/m^2/lux but the difference can be as large as 95 mcd/m^2/lux based on the collected data. The results indicated that the lower average retroreflectivity value for a yellow centerline, measured in the opposite direction from the direction of paint striping, should be used to compare with the future FHWA minimum standard to determine whether or not the centerline meets the standard.

We developed a computer-aided counting method to analyze glass bead images to obtain glass bead density values. Then, we conducted a correlation study between pavement marking retroreflectivity and bead density. The study found that the normal range of bead density we observed was 9-24 percent of the paint marking surface. Bead density had a significant impact on marking retroreflectivity. Higher glass bead density led to higher marking retroreflectivity. Furthermore, white edge markings had conclusively higher retroreflectivity values than yellow center markings when the bead density values were the same.

The study used ANOVA and longitudinal data analysis method to investigate the impact of region on pavement marking retroreflectivity. The results show that in the mountain area the thermoplastic pavement marking retroreflectivity values degraded faster than in the central and coastal area. But, the differences were not statistically significant because the variations within each region were relatively large.

10.2 Retroreflectivity Degradation Models

This research reviewed previously-established pavement marking retroreflectivity degradation models in the literature and identified the modeling methods used in those studies. Based on the marking retroreflectivity data collected on thermoplastics and paints in NC, we established linear regression models and linear mixed effects models for thermoplastics and paints, respectively.

Linear regression models were developed for thermoplastics on asphalt. The independent variables in the model included time, initial retroreflectivity reading, AADT, color, and lateral location, which were all validated by statistical effects tests. The research found that for an AADT of 10,000 vehicles per day, the expected service life for thermoplastics on asphalt ranged from 5.4 years to 8.75 years depending on the color and lateral location. The result also showed that AADT had a small but significant impact on the degradation of thermoplastic pavement markings.

We established linear mixed effects models (LMEM) for white edge and yellow center pavement markings. The LMEM results showed that the fixed intercept and fixed slope were 310 $mcd/m^2/lux$ and -75 $mcd/m^2/lux$ per year for white edge new markings, and were 143 $mcd/m^2/lux$ and -25 $mcd/m^2/lux$ per year for yellow center new markings. The random intercepts and slopes vary in a wide range among different pavement markings, which means that marking performance changed significantly from one road to another. The estimated average lifecycles for white and yellow paint markings were 2.7 and 3.1 years, respectively.

10.3 Pavement Marking Asset Management System

The research developed a transportation asset management system framework for estimating the current and future condition of pavement markings. We described the data structure, in the form of a physical model, integrating a pavement marking relational data schema with existing information technology systems. The system included an algorithm which implements the data structure and predictive models to estimate the condition of the asset at any point in time or space on the highway system. Using either measured data or predicted data, the system gives managers an opportunity to decide on the best possible condition state of the asset and to perform queries or optimizations. Pavement marking managers can develop cost effective strategies for pavement marking asset management.

The transportation asset management system includes AADT, time, and initial R_L as critical variables. AADT is readily available to most highway agencies. Installation date directly relates to time and is a must-have for predictive models. Both installation date and initial R_L readings need to be collected for use in the predictive models. This study highlights how important it is for a highway agency to have good protocols for collecting and maintaining initial R_L data for effective asset management of pavement markings.

11.0 RECOMMENDATIONS

The recommendations in this report are divided into four different subsections which are Pavement Marking Retroreflectivity Data Collection, Glass Bead Density, Pavement Marking Management, and Future Research.

11.1 Pavement Marking Retroreflectivity Data Collection

Based on the results of the lateral line location study (Chapter 2), paint marking directionality study (Chapter 3), and the degradation model studies (Chapters 7 and 8), the following recommendations are made regarding future retroreflectivity data collection. First, future retroreflectivity data collection should consider edge lines and centerlines separately because the centerlines are found to degrade faster than edge lines. The lateral location study result indicated that there was a significant difference in the rate of retroreflectivity degradation between edge lines and centerlines for both yellow and white thermoplastic markings.

Second, the retroreflectivity data for paint pavement marking centerlines on two lane highways should be collected in both travel directions. The lower average retroreflectivity value for a yellow centerline, measured in the opposite direction from the direction of paint striping, should be used to compare with the future FHWA minimum standard to determine whether or not the centerline meets the standard.

Third, future studies should consider collecting paint retroreflectivity data for more than 3 years and thermoplastic data for more than 8 years to have more accurate pavement marking retroreflectivity degradation curves for an entire lifecycle. We recommend that the NCDOT continue collecting data on the 25 “new” paint sites on which we have collected four rounds of retroreflectivity data for at least another year if possible.

Fourth, more marking retroreflectivity data should be collected on other types of marking materials such as polyurea and epoxy. This research focused on the thermoplastics and paints because thermoplastics and paints make up majority of pavement marking mileages, but retroreflectivity readings for other types of materials are limited.

Finally, we highly recommended that the NCDOT record installation date and collects initial retroreflectivity readings for all new pavement markings. The age of the markings and initial R_L readings need to be collected for use of the prediction models. Those data are needed to predict the marking performance on a specific road.

11.2 Glass Bead Density

The research results in Chapter 4 clearly indicate that glass bead density has a significant impact on paint marking retroreflectivity. Higher glass bead density leads to higher marking retroreflectivity. By examining the glass bead density, traffic engineers and researchers can understand how and why pavement marking retroreflectivity readings degrade over time.

The research team recommends that the NCDOT start using the Matlab program to inspect the glass bead densities of newly applied pavement markings to decide if the bead density values are in a normal range (9-22% for paint markings), especially when the retroreflectivity readings of the markings are found to be lower than the NCDOT specified values.

11.3 Pavement Marking Management

We have established retroreflectivity degradation models for thermoplastic and paint pavement markings in Chapters 7 and 8. The FHWA is expected to publish pavement marking retroreflectivity minimum standards in the near future. It is impractical for NCDOT to measure all the pavement markings in NC. We recommend that NCDOT start using the degradation models to predict the marking retroreflectivity values on roads it cannot measure. It is also recommended that NCDOT continue to use a visual inspection process in their management of pavement markings. Visual inspection can be used to verify the condition estimates produced by the models.

This study has presented solutions for data integration issues and Chapter 9 presented an integrated transportation asset management system for estimating the current and future condition of pavement markings as a transportation asset. The research team recommends that NCDOT should hire a private contractor to build the pavement marking management system described in Chapter 9 and integrate the system into the existing asset management system. NCDOT should start to use the system to manage marking retroreflectivity data collection, the schedule for marking restriping, and the pavement marking budget process.

11.4 Future Research

The future research ideas listed below would make more useful information available for pavement marking management in NC.

- The bead density program (BDAP) developed as a part of this study could be improved. The objective of the future research is to pursue an automatic image recognition program.
- An important result of this research was that the initial retroreflectivity measurement of new markings is a very important factor that determines how long markings can last. Future research should be launched to explore how to improve the marking installation process to achieve higher initial retroreflectivity readings.
- This research established thermoplastic and paint marking degradation models. Future research should be initiated to develop degradation models for other types of marking materials (such as polyurea on concrete surfaces) when and where more retroreflectivity data are available.
- The pavement marking asset management system developed in this research should be implemented in the future and the effectiveness of such a system should be evaluated.

12.0 IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

The following outlines how NCDOT and other agencies can use the products developed as part of the research to improve pavement marking management in North Carolina and beyond.

12.1 Research Products

The research products developed as a result of this research project include:

- Evaluation of pavement marking R_L impacting factors.
- A Matlab program (BDAP) for determining image bead density values.
- The set of recommendations given in Chapter 11 of this report.
- Field paint pavement marking data collected in four NCDOT Divisions (Appendix A).
- R_L degradation models developed for thermoplastic and paint pavement markings.
- The pavement marking asset management system presented in Chapter 10.
- Six peer reviewed journal papers:
    - Craig, N., Sitzabee, W., Rasdorf, W., and Hummer, J., "Statistical Validation of the Effect of Lateral Line Location on Pavement Marking Retroreflectivity Degradation," Journal of Public Works Management and Policy, American Public Works Association, Volume 12, Number 2, Pages 431-450 (October 2007).
    - Sitzabee, W., Rasdorf, W., Hummer, J., and Devine, H., "Pavement Marking Data Model: A Case for Asset Management," Journal of Computing in Civil Engineering, American Society of Civil Engineers (2009). Accepted.
    - Sitzabee, W., Hummer, J., and Rasdorf, W., "Pavement Marking Degradation Modeling and Analysis," Journal of Infrastructure Systems, American Society of Civil Engineers (2009). Accepted.
    - Rasdorf, W., Zhang, G., and Hummer, J., "The Impact of Directionality on Paint Pavement Marking Retroreflectivity," Journal of Public Works Management and Policy, American Public Works Association, Volume 13, Number 3, Pages 265-277 (January 2009).
    - Zhang, G., Hummer, J., and Rasdorf, W., "The Impact of Bead Density on Paint Pavement Marking Retroreflectivity," Journal of Transportation Engineering, American Society of Civil Engineers (2009). Submitted 5-15-2009.
    - Hummer, J., Rasdorf, W, and Zhang, G., "Linear Mixed Effects Model for Paint Pavement Marking Retroreflectivity Data," Journal of Transportation Engineering, American Society of Civil Engineers (2009). To be submitted.

12.2 Research Products Users

The following groups within the NCDOT can apply the research products to inform and improve their decisions and policies:

- Work Zone Traffic Control Unit
- Division Traffic Services
- State Road Maintenance Unit
- Asset Management

In addition, the research products can be useful to other departments of transportation, the FHWA, and other agencies involved in the areas of pavement marking and asset management.

12.3 Research Products Application

The NCDOT and others outside the department can use the research products named in Section 12.1 to advance pavement marking management and other areas. The recommendations in Chapter 11 can be applied across the NCDOT to inform pavement marking maintenance budgeting and management, such as deciding how often to restripe pavement markings.

The paint pavement marking retroreflectivity data collected as part of this research are valuable to the NCDOT, FHWA, and other agencies that are involved in research in pavement marking performance and maintenance. The developed thermoplastic and paint pavement marking degradation models are valuable tools that NCDOT can use to predict pavement marking performance based on initial retroreflectivity readings.

A Matlab program (BDAP) has been developed for determining image bead density values. A two-hour training session is need for a traffic engineer to learn how to use the program. The research team is willing to meet with any NCDOT group that would like to learn more about the program and other products of this research.

Finally, the journal papers written as results of this research project advance our overall knowledge of pavement marking performance. The papers disseminate the research findings to transportation agencies and research community.

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14.0 APPENDICES

The appendices include the paint pavement marking retroreflectivity data and the trip reports for the project.

14.1 Paint Retroreflectivity Data

The research team began collecting paint retroreflectivity data in November 2007. We measured 40 sample sites. The paint markings on 25 roads were installed in 2007 and were two to three months old when we conducted the first measurement. The markings on the other 15 roads were installed in 2006 and were about 20 months old.

Table 14.1 lists the locations of the forty sampling sites. There are 5, 12, 15, and 8 roads located in Divisions 3, 4, 5, and 7, respectively. The shaded rows in Table 14.1 are older paint markings installed in 2006. Figure 14.1 shows the measuring locations on a GIS map. The measured sites are all located in the central area of North Carolina.

Tables 14.2-14.5 show the four rounds of paint data we collected on the 40 sites. From the third round of data collection, we found that one road (No. 3, Lochridge Rd.) was restriped with paints. Another road (No. 12, Gilcrest Farm Rd.) was restriped with thermoplastics. We abandoned one site (No. 4, Island Creek Rd.) for safety reasons (dogs) in the third round of data collection.

Table 14.1. Paint Data Collection Location Information

No.	Div	County	Road Name	Date Installed	1st Reading Date	2nd Reading Date	3rd Reading Date	4th Reading Date
1	5	Vance	Egypt Mtn Rd	9/26/2007	11/16/2007	5/21/2008	12/5/2008	5/14/2009
2	5	Vance	Aycock School	9/27/2007	11/17/2007	5/21/2008	12/5/2008	5/18/2009
3	5	Vance	Lochridge Rd	8/22/2007	11/16/2007	5/21/2008	12/5/2008	5/18/2009
4	5	Vance	Island Ck Rd	8/22/2007	11/17/2007	5/21/2008	12/5/2008	5/18/2009
5	5	Franklin	NC 581	9/10/2007	11/19/2007	5/20/2008	12/1/2008	5/15/2009
6	5	Franklin	Preacher Ball	9/10/2007	11/20/2007	5/20/2008	12/1/2008	5/15/2009
7	5	Franklin	Mitchell Store	9/13/2007	11/21/2007	5/19/2008	11/28/2008	5/12/2009
8	5	Franklin	Robbins Rd	9/13/2007	11/21/2007	5/19/2008	11/28/2008	5/12/2009
9	5	Franklin	Bob Richards Rd	9/17/2007	11/27/2007	5/19/2008	11/28/2008	5/12/2009
10	5	Franklin	Alford Mill Rd	9/18/2007	11/20/2007	5/20/2008	11/29/2008	5/12/2009
11	5	Franklin	Dunn Rd	9/18/2007	11/20/2007	5/20/2008	12/1/2008	5/15/2009
12	5	Franklin	Gilcrest Farm	9/19/2007	11/28/2007	5/19/2008	12/1/2008	5/14/2009
13	5	Franklin	Pine Ridge Rd	3/1/2006	1/26/2008	5/19/2008	11/29/2008	5/12/2009
14	5	Franklin	Tant Rd	3/1/2006	1/26/2008	5/19/2008	11/29/2008	5/12/2009
15	5	Durham	Interworth Rd	2/28/2006	1/4/2008	5/23/2008	12/5/2008	5/18/2009
16	4	Nash	Swift Creek Rd	10/9/2007	11/30/2007	5/20/2008	12/1/2008	5/13/2009
17	4	Nash	Straight Gate	10/9/2007	11/29/2007	5/20/2008	12/1/2008	5/15/2009
18	4	Nash	Claude Lewis Rd	10/11/2007	11/29/2007	5/27/2008	12/12/2008	5/24/2009
19	4	Nash	Finch Rd	10/15/2007	11/29/2007	5/27/2008	12/12/2008	5/24/2009
20	4	Johnston	Matthews Rd	10/23/2007	12/14/2007	5/27/2008	12/13/2008	5/24/2009
21	4	Johnston	Branch Chapel	10/23/2007	12/14/2007	5/27/2008	12/12/2008	5/20/2009
22	4	Johnston	North Pleasant-	10/17/2007	12/14/2007	5/27/2008	12/13/2008	5/24/2009
23	4	Johnston	Railroad Ave.	7/19/2006	1/8/2008	5/29/2008	12/13/2008	5/20/2009
24	4	Wayne	Sevens Mill Rd	7/17/2006	1/8/2008	5/29/2008	12/13/2008	5/20/2009
25	4	Wayne	Kelly Springs Rd	7/13/2006	1/8/2008	5/29/2008	12/13/2008	5/20/2009
26	4	Wayne	Airport Rd	7/7/2006	1/8/2008	5/29/2008	12/13/2008	5/20/2009
27	4	Wayne	Jordan Chapel	8/8/2006	1/8/2008	5/29/2008	12/13/2008	5/20/2009
28	7	Orange	University	10/8/2007	12/20/2007	5/22/2008	12/6/2008	5/22/2009
29	7	Orange	Murphey School	10/9/2007	12/20/2007	5/22/2008	12/6/2008	5/22/2009
30	7	Orange	Cornwallis Rd	10/9/2007	12/20/2007	5/22/2008	12/6/2008	5/22/2009
31	7	Orange	Brockwell Rd	10/11/2007	12/20/2007	5/22/2008	12/6/2008	5/22/2009
32	7	Orange	Kerley Rd	11/14/2007	12/19/2007	5/22/2008	12/6/2008	5/22/2009
33	7	Orange	Buckhorn Rd	11/1/2007	12/20/2007	5/23/2008	12/7/2008	5/14/2009
34	7	Alamance	Elon-Ossippe Rd	4/7/2006	1/4/2008	5/23/2008	12/7/2008	5/14/2009
35	7	Alamance	Rumley RD	4/17/2006	1/4/2008	5/23/2008	12/7/2008	5/14/2009
36	3	Sampson	Register Sution	7/7/2006	1/27/2008	5/30/2008	12/14/2008	5/19/2009
37	3	Sampson	Dunn Rd	5/5/2006	1/27/2008	5/30/2008	12/14/2008	5/19/2009
38	3	Sampson	Bearskin Rd	3/3/2006	1/27/2008	5/30/2008	12/14/2008	5/19/2009
39	3	Sampson	Hobbs Rd	3/20/2006	1/27/2008	5/30/2008	12/14/2008	5/19/2009
40	3	Sampson	Hoover Rd	5/25/2006	1/27/2008	5/30/2008	12/14/2008	5/19/2009

Note: 15 shaded rows are older painted markings installed in 2006.
25 white rows are newer painted markings installed in 2007.

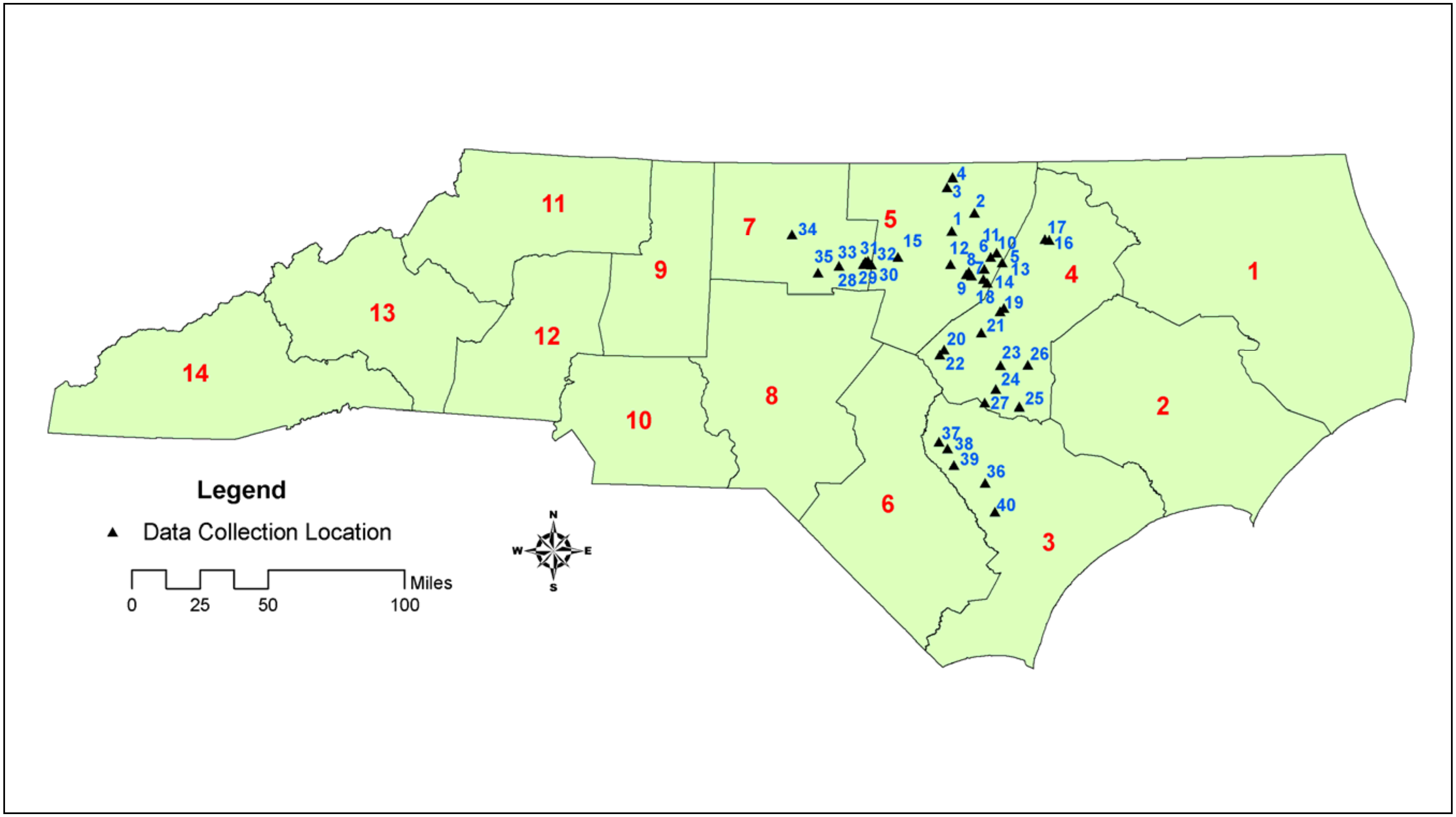

Figure 14.1. Paint Data Collection Locations

Table 14.2. First Round Retroreflectivity Readings (in mcd/m^2/lux)

No.	Days Old	W. Edge Ave.	Y. Cent. Ave.	W. Edge	Yellow Center		Yellow Center		W. Edge
				↓	↓	↑	↓	↑	↑
1	51	239	94	226	77	-	-	110	252
2	51	244	114	243	97	-	-	130	245
3	86	333	128	318	152	-	-	104	348
4	87	282	158	326	175	-	-	141	237
5	70	185	132	201	120	-	-	143	169
6	71	358	161	399	159	-	-	162	316
7	69	382	96	406	130	-	-	62	358
8	69	221	89	296	43	-	-	134	145
9	71	338	95	326	122	-	-	68	349
10	63	331	70	333	31	-	-	109	328
11	63	441	103	460	90	-	-	115	422
12	70	368	181	379	183	-	-	178	356
13	696	220	108	197	99	126	97	112	242
14	696	206	140	200	130	155	129	145	213
15	675	218	74	206	54	107	50	85	230
16	52	379	216	401	197	-	-	235	356
17	51	240	167	256	190	208	130	140	224
18	49	247	126	230	133	146	100	124	263
19	45	269	119	273	106	93	145	131	264
20	52	344	122	361	157	138	99	94	326
21	52	415	178	382	174	160	199	180	447
22	58	355	207	346	205	212	198	212	364
23	538	176	114	209	103	143	88	120	144
24	540	310	202	309	217	211	196	183	311
25	544	284	174	264	168	162	189	179	303
26	550	210	102	185	101	98	120	91	235
27	518	215	54	215	46	69	44	59	214
28	73	286	144	280	148	103	136	190	292
29	72	259	137	273	109	147	118	172	245
30	72	378	201	362	238	213	195	159	394
31	70	129	166	118	127	162	170	205	139
32	35	337	179	301	192	167	194	164	373
33	49	211	132	242	103	160	100	166	179
34	637	356	163	358	145	167	153	184	354
35	627	296	165	313	188	144	187	144	278
36	569	183	76	152	64	92	61	86	215
37	632	149	116	149	116	82	142	123	149
38	695	154	103	162	110	118	91	93	147
39	678	131	71	187	65	58	87	75	76
40	612	124	78	132	102	53	105	50	117

Note: W. Edge represents White Edge;
W. Edge Ave. represents White Edge Average;
Y. Cent. Ave. represents Yellow Center Average.
Shaded rows are older painted markings installed in 2006.
"-" means that the values were not measured.

Table 14.3. Second Round Retroreflectivity Readings (in mcd/m^2/lux)

No.	Days Old	W. Edge Ave.	Y. Cent. Ave.	W. Edge	Yellow Center		Yellow Center		W. Edge
				↓	↓	↑	↓	↑	↑
1	238	237	91	216	71	135	50	107	257
2	237	210	102	216	78	140	72	119	205
3	273	298	118	307	150	111	118	94	289
4	273	250	124	276	138	127	124	108	224
5	253	128	95	141	92	117	77	92	116
6	253	262	149	240	137	109	185	166	284
7	249	245	89	239	102	62	124	69	251
8	249	235	99	198	124	76	128	70	271
9	245	288	85	272	59	121	61	99	305
10	245	193	69	196	83	48	93	54	189
11	245	316	98	313	90	103	89	109	318
12	243	310	96	265	90	79	116	100	356
13	810	207	100	244	104	89	118	90	171
14	810	204	148	205	153	137	162	140	202
15	815	238	68	247	76	48	91	57	229
16	224	301	194	304	175	195	195	213	298
17	224	189	149	198	168	114	187	126	181
18	229	195	94	176	97	76	110	93	214
19	225	212	95	200	77	113	78	111	224
20	217	272	117	271	149	127	107	86	272
21	217	339	172	320	148	149	212	181	359
22	223	323	190	292	182	196	185	199	355
23	680	180	111	206	95	147	83	121	153
24	682	328	215	325	232	226	206	197	331
25	686	308	195	288	190	184	208	198	328
26	692	209	96	179	96	89	114	85	238
27	660	186	97	185	73	124	73	116	186
28	227	274	113	256	87	134	92	138	291
29	226	247	126	242	159	101	144	101	252
30	226	320	184	331	149	178	193	214	309
31	224	125	157	107	114	155	160	199	142
32	190	250	140	261	128	141	135	158	238
33	204	218	126	221	105	150	98	152	215
34	777	345	154	326	168	144	162	142	364
35	767	274	178	261	153	204	152	203	288
36	693	177	78	174	65	96	63	88	179
37	756	150	124	140	122	97	144	133	160
38	819	149	118	155	128	136	107	103	144
39	802	137	76	86	78	93	60	72	188
40	736	120	81	110	53	114	51	104	131

Note: W. Edge represents White Edge;
W. Edge Ave. represents White Edge Average;
Y. Cent. Ave. represents Yellow Center Average.
Shaded rows are older painted markings installed in 2006.

Table 14.4. Third Round Retroreflectivity Readings (in mcd/m^2/lux)

No.	Days Old	W. Edge Ave.	Y. Cent. Ave.	W. Edge	Yellow Center		Yellow Center		W. Edge
				↓	↓	↑	↓	↑	↑
1	436	219	91	206	134	70	105	54	232
2	435	230	102	245	137	74	123	73	215
3*	-	316	148	342	164	117	188	124	291
4	471	-	-	-	-	-	-	-	-
5	448	99	87	120	111	80	87	69	79
6	448	245	128	247	163	146	123	79	243
7	442	228	92	213	66	110	68	123	243
8	442	184	94	237	124	65	116	71	131
9	438	254	90	290	122	74	100	64	218
10	438	165	66	159	46	77	51	89	171
11	440	284	119	259	131	104	135	105	310
12*	-	298	187	295	174	168	204	203	301
13	1004	154	69	115	84	59	75	60	193
14	1004	201	136	219	147	128	136	133	183
15	1011	190	64	198	93	49	75	40	182
16	419	303	176	363	183	156	199	165	244
17	419	130	157	116	120	170	137	198	144
18	428	185	92	168	76	96	93	105	202
19	424	199	82	169	65	87	68	107	229
20	417	265	136	276	155	167	107	114	254
21	416	342	207	366	162	199	214	252	317
22	423	286	201	248	208	189	210	196	325
23	878	177	116	207	150	99	120	95	147
24	880	309	214	309	216	203	225	214	308
25	884	301	204	242	202	192	208	214	359
26	890	194	69	147	63	62	65	84	241
27	858	180	84	181	114	65	98	59	179
28	425	278	110	284	87	133	90	129	272
29	424	264	121	263	140	94	151	98	266
30	424	323	178	302	207	228	122	157	345
31	422	126	138	96	132	93	172	155	156
32	388	222	123	226	126	113	117	136	218
33	402	168	96	167	72	111	83	119	170
34	975	342	158	357	150	163	152	169	327
35	965	251	172	233	193	152	198	147	268
36	891	174	66	182	81	55	73	54	167
37	954	155	120	149	89	106	141	145	161
38	1017	133	103	137	120	110	89	94	130
39	1000	117	66	164	55	60	70	80	69
40	934	112	75	102	106	51	91	50	123

Note: W. Edge represents White Edge;
W. Edge Ave. represents White Edge Average;
Y. Cent. Ave. represents Yellow Center Average.
15 shaded rows are older painted markings installed in 2006.
25 white rows are newer painted markings installed in 2007.
"-" means that the values were not measured.
No 3 and No 12 roads have been restriped.

Table 14.5. Fourth Round Retroreflectivity Readings (in mcd/m^2/lux)

No.	Days Old	W. Edge Ave.	Y. Cent. Ave.	W. Edge	Yellow Center		Yellow Center		W. Edge
				↓	↓	↑	↓	↑	↑
1	596	187	75	178	115	56	83	47	196
2	599	181	83	189	125	74	67	67	173
3*	635	177	115	207	131	106	138	87	147
4	635	145	69	137	61	78	57	79	153
5	613	68	68	87	84	66	66	55	50
6	613	213	130	220	173	144	115	89	205
7	607	163	78	160	56	97	54	106	166
8	607	162	77	189	96	53	102	57	135
9	603	204	66	181	50	77	49	87	226
10	602	133	52	134	39	59	39	71	132
11	605	234	107	202	108	91	125	103	266
12*	603	248	119	204	113	98	127	139	293
13	1168	140	62	95	71	53	67	56	185
14	1168	164	108	168	116	100	117	101	160
15	1175	142	58	149	82	48	65	37	134
16	582	271	155	302	158	134	170	159	241
17	584	113	136	100	101	148	119	175	127
18	591	175	80	164	68	84	80	90	186
19	587	156	65	139	50	72	51	87	172
20	579	225	123	216	141	152	97	103	234
21	575	221	169	263	142	153	203	179	179
22	585	233	156	289	146	163	148	167	177
23	1036	151	102	185	131	91	106	78	117
24	1038	308	215	294	217	197	225	220	322
25	1042	300	192	263	184	181	196	208	336
26	1048	138	49	108	47	43	51	56	167
27	1016	146	70	143	93	51	85	50	149
28	592	232	100	211	122	81	117	82	252
29	591	245	117	235	96	141	94	138	254
30	591	246	150	237	142	113	186	159	255
31	589	99	120	79	115	89	153	122	119
32	555	187	114	179	115	105	121	117	194
33	560	147	83	137	70	96	68	96	156
34	1133	253	116	227	109	125	105	127	279
35	1123	217	162	227	186	144	180	140	206
36	1047	124	60	157	76	50	67	48	91
37	1110	120	103	115	74	90	118	131	125
38	1173	105	92	107	108	102	76	81	102
39	1156	111	55	159	48	51	59	62	63
40	1090	90	67	85	94	47	82	45	96

Note: W. Edge represents White Edge;
W. Edge Ave. represents White Edge Average;
Y. Cent. Ave. represents Yellow Center Average.
15 shaded rows are older painted markings installed in 2006.
25 white rows are newer painted markings installed in 2007.
No 3 and No 12 roads have been restriped.

14.2 Trip Reports

The trip reports provide details about trips conducted for the purpose of this research project.

14.2.1 Signs and Pavement Markings Asset Management Meeting Notes

August 10, 2007 1:30 pm – 3:00 pm Room 104, Highway Building

Attendees

NCSU: Elizabeth Harris, William Sitzabee NCDOT: Terry Canales, Lacy Love

Traffic Units, Asset Management(AM), Road Maintenance, and Division Traffic Services all deal with signs and Pavement Marking(PM) management.

NCDOT divides division funding into primary roads, secondary roads, general maintenance reserve, and system preservation (targeted categories such as pavement, signal, and bridge maintenance) buckets. Special item funding can be designated by the board of transportation to go towards inmate work crews, condition assessment, and emergency funds. Once designated, funds can not be moved from one bucket to another. However, funds can be balanced within a functional bucket.

The amount given to each division for operations and maintenance is typically based on historical operations and maintenance costs and the number of division lane miles and bridges. A division may request more money in anticipation of certain needs for the coming year. In the future, AM would like to use some of the performance measures to guide budgeting also. There are no direct allocations at the state level for signs and PM maintenance/installation. Funds are distributed every year, but NCDOT is considering moving towards a 2 year or longer work plan. Right now divisions/NCDOT can carry to the next year any O&M funds not spent in the previous fiscal year.

TIP funding is distributed using the equity formula. Condition assessment data is used to convince legislature that funds are needed. MPOs, STIP, and the board of transportation also have some influence over funding/distribution.

Condition assessment conducted by NCDOT maintenance units is paid for out of the maintenance fund. Condition assessment is conducted every 2 years, except for interstate pavements which are inspected annually.

The condition assessments will be used by the Maintenance Management System (MMS) to analyze performance measures, function codes, tasks/work orders and to provide an “ideal” work plan. The MMS can determine how much funding it would take to reach a certain performance target or what performance level can be reached with certain amount of funding. The MMS can help identify deficiencies and target spending to high priority needs.

Right now in the MMS, ground mounted signs have a priority of 8 and overhead signs a priority of 6 on a scale from 1 to 9.

Divisions will become accountable for their performance levels beginning in 2008. However, the first few cycles will be used to establish a benchmark of the condition with an intent to evaluate fluctuations in the condition of the asset.

Along with the implementation of the MMS/condition assessment program, NCDOT is planning to implement a new tiered road system for budgeting, maintenance, and management called the DOT Multimodal Long Range Transportation Plan. The Statewide tier consists of 5,400 miles of major roads, including the strategic highway corridors and major hubs. The regional tier will consist of US and NC routes, along with high traffic/critical secondary routes. The subregional tier will include all other secondary roads. Performance measure targets will be higher on statewide tier roads and the lowest on subregional tier roads. For example, the performance goal for signs on the statewide tier is 92% and 95% for pavement markings.

NCDOT AM would like to quantitatively assess all assets on the statewide tier roads. This may be difficult for signs, which will probably require sampling instead. For the regional and subregional tiers, the current visual condition assessment will suffice. The visual condition assessment looks at whether signs and PM are visible and legible at night. It may be desirable for a complete collection of pavement marking retroreflectivity data for the state wide tier.

There is a Transformation Team at NCDOT currently working on how the DOT can be restructured. Moving pavement marking management out of WZTCU was offered as a possible area to consider.

The NCDOT would like to move towards more proactive and less reactive maintenance and more responsibility on the divisions to maintain a high level of performance.

14.2.2 Division 6 Traffic Services Meeting Notes

August 13, 2007 1:00 pm – 3:00 pm Conference Room, Century Center

Attendees

NCSU: Elizabeth Harris, William Sitzabee NCDOT: Kent Langdon, Lee Jernigan

The division requests money based on historical data, available manpower, material costs, and extra work the division wants to accomplish in the coming year. Traffic services drafts up a spending and work plan by function code that is then forwarded to the division.

The division then requests primary and secondary funds by county. This money is then sent to the division traffic services. The division traffic services decides how much money goes towards signs and PM work functions by county. Usually, most of the primary money goes towards signs because PMs on primary roads are paid for through marking contracts (thermoplastic). The division uses paint and preformed thermoplastic symbols only.

Funds can be shifted among counties if needed, but not between primary and secondary roads. If the division runs low on funds at the end of the year (December) there is a holiday/maintenance break.

Division 6 has been preventatively upgrading Type I signs to Type III on US and NC routes because there was some extra funding made available only for primary routes maintenance, which the division could not use on PM because primary roads have thermoplastic PM.

Pavement is resurfaced in the division on a 7-10 year cycle. Division 6 tries to coordinate pavement marking material selection with the pavement resurfacing cycles. If pavement will be resurfaced in the next 1-2 years, then only paint is installed. However, in most cases roads with an AADT of 4000 or greater are typically markied with thermoplastics which are expected to last for the entire life cycle of the pavement (7-10 years).

The divisions look at the MMS results as a tool that they can potentially use to plan maintenance.

The division is quartered and then the pavement marking inspection cycle is set that 2 quarters are visual inspected every year (windshield inspection). Interstates are the exception and they are inspected annually.

All pavement marking operations are tracked via hardcopy. This is done using a color coded system that highlights every road in the division with a color representing when the road was remarked. Div 6 policy is to remark all long lines on a road segment at the same time.

Division 6 has an LTL 2000 but it is used primarily for inspecting contractor performed marking operations on new construction. In house marking operations they do not collect retroreflectivity values. Also, in house markings are accomplished with paint only. Every road is remarked biennially, exceptions are low AADT roads which are remarked not less than every three years.

14.2.3 State Road Maintenance Unit Meeting Notes

August 30, 2007 1:30 to 3:00 pm Conference Room, State Maintenance Unit

Attendees
NCDOT: Lonnie Watkins, Matthew Whitley, and Jon Arnold
NCSU: William Sitzabee, Elizabeth Harris, and Guanghua Zhang

The purpose of this meeting was for the state maintenance unit to give an overview of the maintenance condition assessment program (MCAP) and the Maintenance Management System (MMS) The meeting notes are in two parts. First is a summary of the MCAP and then is a review of the MMS

MCAP
The MCAP is conducted biennially. The last MCAP was conducted in 2006 with the next assessment scheduled for 2008. The purpose of the MCAP is to provide a state-wide condition assessment of all the road side appurtenances. Pavement, bridges and other assets are evaluated under different programs.

The MCAP looks specifically at five elements

1. Unpaved Shoulders and Ditches
2. Drainage
3. Roadside
4. Traffic Control
5. Environmental

Pavement markings fall under the traffic control device element which assesses four subcategories

1. Traffic Signs
2. Pavement Striping
3. Words and Symbols
4. Pavement Markers

The MCAP assessment is a physical inspection where the inspectors walk two tenths of a mile of road segment evaluating all the elements identified above. The total inventory and the condition of each element are recorded on a one page data collection form.

The road segments are picked randomly following the procedures outlined in "the Maintenance Condition Assessment Sampling Study – ITRE Project HWY-0875" dated 10 Mar 2006. The road segments are identified using the universe (GIS) LRS system which is a route-beginning mile post – end mile post system. All the location information, including directions, is pre-printed on the top of the data collection form. The form includes the inspector names, dates, city, county, and division information.

The basic assessment structure is to determine the total amount of a given asset in the road segment and then determine the percent of the assets that are deficient. For pavement markings, the amount of inventory is first defined by determining the total length of pavement striping in the segment. For example, if a typical two-lane roadway is being inspected (with edge lines and double yellow centerlines), the total pavement striping length will be 4,224 feet (0.2 mi x 5,280 ft/mi x 4 solid lines). If assessing a five-lane road (two through lanes each direction with a two-way left-turn lane)the total length will be 5,280 feet (0.2 mi x 2,280 ft/mi x 4 solid lines + 4 broken line at 0.2 mi x 5,280 ft/mi x 10 ft/40 ft). Next the total number of feet that are worn, missing or obliterated is then recorded.

For signs, the total number of signs in the segment are counted and noted as the total segment inventory. The survey does not include overhead signs on structures, street name signs, historic marker signs, non-DOT signs, and logo signs. Where there is a sign assembly, the assembly is counted as one sign. Next, the number of signs that are illegible, missing, or obliterated are counted for the segment and recorded.

The form is then loaded into an Oracle database. This is later translated into an Access database where the state maintenance unit then cleanses the data using a series of SQL queries. For example, a value outside of a logical range would be reviewed and corrected or thrown out.

Finally, the number of deficient feet of the asset (or number of signs) is divided by the total number of feet of asset (or number of signs) to determine the percent deficient. This is then translated into a state wide condition based on the sampling process identified above.

MMS

The MMS is a statewide database that manages all maintenance functions based on functional codes. The MMS is set up by road segment using the same LRS used by the GIS unit (this is the universe file). In all cases, the maintenance work is recorded against a specific road segment using predefined function codes. Currently there are over 400 function codes which are in the process of being consolidated into approximately 100 codes.

The MCAP data is recorded in the MMS and includes an interface with the NCDOT financial database, which records all material and labor costs associated with the road segment. In MMS, queries of road history are much easier than before. Various maintenance related reports can be automatically generated using the system.

The MMS has a built in optimization program. Although it is not functioning correctly yet, state maintenance personnel believe this is a good feature and with quality data this will prove to be a valuable tool. The optimizer has the ability to assess how much money it would take to bring a certain asset up to a given condition.

MMS is felt to be a good system but it is underutilized. Front line work crew supervisors don’t understand the importance of accurate data entry on their behalf because they don’t see the use. Also currently there are no consequences if the supervisors do not use it. This is partly why the function codes are being re-organized and reduced.

It may be possible to link the pavement marking database to the MMS through the universe (GIS) file if the Pavement marking database could align the location referencing systems.

14.2.4 Meeting with NCDOT Work Zone Traffic Control Unit

October 10, 2007 1:00 pm – 2:00 pm. Meeting Room 201-E, Mann Hall, NCSU

Attendees

NCSU: Dr. William Rasdorf, Dr. Joseph Hummer, William Sitzabee, Guanghua Zhang
NCDOT: Chris Howard, Davin Schmidt, Mark Manriquez

The NCSU research team presented a paint data collection plan to the WZTCU. The NCSU research team found the current sample size of paint markings in the database was not adequate to develop valid paint degradation models because the current models do not account for color or lateral location. The research team worked out a paint data collection plan for NCDOT to collect more paint marking retroreflectivity data.

The NCSU researchers explained what they found in the 2007 pavement marking database and presented a preliminary paint linear degradation model. The researchers established time, initial R_L, AADT, color and lateral location as pavement marking variables. NCDOT technicians added that the paint marking width, thickness (mils), and bead type were other factors having an effect on the degradation rate and paint service life. Other contributing factors such as binder, quality control during installation were discussed in the meeting. WZTCU was interested to know how the paint thickness impacted the performance. However the 2007 database did not include the actual installation thickness data.

The research team requested NCDOT WZTCU to help with the future paint data collection and made recommendations for the data collection. WZTCU engineers were supportive of the plan and indicated that they were going to help implement it. WZTCU pointed out that paint on concrete surfaces was not of much interest since their application was limited. They were going to concentrate on the asphalt surfaces and continue the paint data collection which has already begun since April, 2007. WZTCU confirmed that the existing database included only contractor performed paint installation samples, not in-house installed samples. WZTCU agreed that in-house installed paint samples need to be collected in the future to represent the overall paint marking performance.

The research team introduced the statistical method used to determine the sample sizes. If the sample size was below 40 road segments, the estimated R_L range was about ± 20 of the actual R_L value. WZTCU thought the range was not too bad, but did not want to go for larger ranges. Increasing the sample size was a method to reduce the range. With an estimated degradation rate of 4.17 mcd/m^2/lx per month a range of ± 25 equates to approximately one year in terms of life cycle.

Mr. Mark Manriquez introduced NCDOT incentive program for in-house paint applications and explained the inspection program. About 10% of paint markings were inspected by the program. Five percent was the nighttime visual inspection and another 5% was daytime R_L reading. The inspection date was within one year after installation. Mr. Manriquez diligently followed up by sending the inspection data sheets after the meeting.

14.2.5 Meeting with NCDOT GIS/IT unit

October 24, 2007 from 12:00 to 1:30 pm, Conference Room at the NCDOT GIS Unit
3401 Carl Sandburg Court, Raleigh, NC 27606

Attendees

NCDOT: Ray Chilcote, Chris Tilley, John Farley
NCSU: William Sitzabee, William Rasdorf, Joseph Hummer, and Guanghua Zhang

Purpose of Meeting

The purpose of this meeting was to present the proposed physical model for data integration and confirm all the right components were present. Additionally, we wished to designate and understand all the relationships within the model.

Meeting Notes

- The proposed Physical Model was presented and all the components and relationships were discussed. The NCDOT GIS unit agreed that all the right components existed with the exception of an LRS filter. The relationships between components were discussed and confirmed.
- All agreed that MMS is the place to add the pavement marking data
- The GIS unit confirmed that this is a good data integration model and will build on the existing system very easily.
- The NCDOT IT/GIS unit has Visio but is moving to using Enterprise Architect. They bought 20 copies and plan to implement in the near future.
- GIS unit will send Sitzabee a clean road file that is routable to use with his GIS example.
- AIA (Agile) is the contractor responsible for the MMS.

In a follow-up meeting with AIA on 1 Nov at 1300 hrs at AIA local office on Atlantic Ave., Sitzabee met with Charles Pilson, contact number 919-573-5217.

- MMS is going to a web-based version
- MMS is an Oracle database and the EA generated XML file will import into the MMS. Format of the file works but access is proprietary and NCDOT will need to authorize the implementation of the XML file and pay for it.
- Instead of using the XML file, MMS has front-end software capability to implement the tabular structure. The advantage of using this software is that it will construct and populate the corresponding windows and menus in MMS. If this is done via XML, the windows and menus would have to be constructed manually.
- MMS has built in optimization software that is focused at maintaining a steady state (how much money to keep us at this level). The PMS system is similar to the MMS but has built in optimization software that addresses deterioration optimization. PMS falls under pavements where as MMS falls under state maintenance.

14.2.6 Pavement Marking Rodeo Trip Report

Date: February 06, 2008 7:30 am – 4:30 pm
Location: James B. Hunt Horse Complex, NC State Fairgrounds in Raleigh
Contacts: Rodeo Attendees

The North Carolina Department of Transportation (NCDOT) Work Zone Traffic Control Unit (WZTCU) hosted a pavement marking rodeo on February 05 and 06, 2008. The research team member G. John Zhang attended the February 06 training sessions. The research project PI and co-PI Dr. William Rasdorf and Dr. Joseph Hummer attended a portion of the rodeo along with another team member William Sitzbee.

Six sessions were provided in the rodeo and each session lasted 50 minutes. The topics of the sessions covered different aspects of the pavement marking practices in N. C. The session topics were:

- Paint
- Molten thermoplastic installation
- Polyurea, epoxy and profiled marking installation
- Pavement marking tapes, markers, and heated in place thermoplastic
- Glass beads, inspection procedures, and retroreflectometers
- Traffic control for pavement marking installation

Overall the rodeo provided a very good training both for pavement marking technicians and researchers. Technicians were able to learn some theoretical considerations behind pavement marking practices, while researchers had an opportunity to inspect the equipment and talk with the technicians that use it. Some information relevant to the research project is summarized in the following paragraphs.

Polyurea is superior to epoxy because polyurea has better color retention and bonding characteristics. Polyurea also has a shorter curing time. Currently NCDOT pavement marking policy is using polyurea on concrete surfaces and using epoxy on roads west of I-77 when polyurea is not an alternative.

Paint is normally installed in two runs on the two-lane highways. The first run can stripe three lanes of paint, one white edge lane and two yellow center lanes. The second run stripes another white edge lane in the opposite direction. Two applications of 15-18 wet mil thickness paint are needed on new pavement surfaces. The second application is to compensate for paint that is absorbed into the pavement during the first application. There is no specific requirement on how long the interval between the two applications should be.

Glass beads provide the best retroreflection when 40% of the bead is exposed above the marking and 60% is embedded in the marking. Putting too many beads on the marking can actually decrease the retroreflectivity of the line.

A speculative reason for why paints have retroreflectivity directionality (R_L values in one direction are higher than the opposite direction) is that the glass beads have a horizontal velocity when sprayed from a pressured dispenser. Figure 14.2 (A) shows an ideal paint application. The retroreflectivity from both traffic directions would be same. Figure 14.2 (B) shows a practical paint surface. The glass beads may have more paint resin covering their surfaces in one direction than the other because the beads are sprayed from a moving truck traveling at a speed of 10-12 mph. More head light may enter and be retroreflected back from the glass bead from one direction than the other.

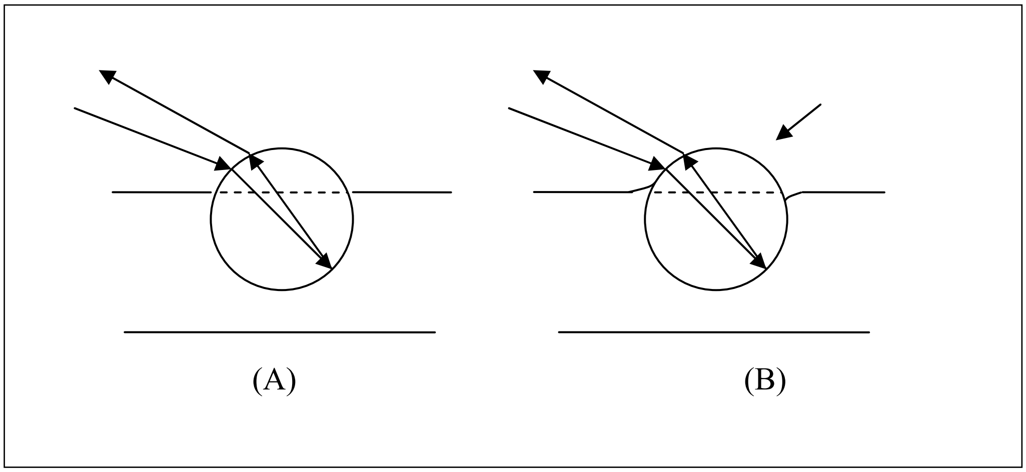

Figure 14.2. Bead Embedment Illustration

On a typical restriping project, NCDOT requires that three portions of pavement marking should be inspected after installation. The three portions should be located at the beginning, middle and end of the project. Each portion should have 6 measurements of the retroreflectivity on each line. If the average of the six readings is below the minimum values required in Table 14.6, then the readings should be taken for each 1000-foot interval.

Table 14.6. NCDOT Initial R_L Requirement Measured with LTL2000 and LTL-X

Time	Paint		Thermoplastics		Polyurea and Epoxy with Standard beads		Permanent Standard Tape	
	White	Yellow	White	Yellow	White	Yellow	White	Yellow
Initial	225	200	375	250	375	250	400	300
180 Days	200	180	325	200	325	200	-	-

14.2.7 Division Six Paint Truck Operation Trip Report

Date: March 05, 2008 7:00 am – 3:00 pm
Location: 450 Transportation Dr., Fayetteville, NC 28302
Contacts: C. L. (Bo) McMillian, (910)486-1452, clmcmillian@dot.state.nc.us
William Faircloth, (910)486-1452, wjfaircloth@dot.state.nc.us

With the help of NCDOT Division 6 pavement marking supervisor Mr. McMillian and engineer William Faircloth, project team member G. John Zhang visited the Division 6 traffic service office on March 05, 2008. The objective was to investigate and understand the paint truck operation and division pavement marking management practices.

Division 6 recently purchased two new MB paint trucks to replace their two 12 year old trucks. The new paint trucks are similar to the old trucks except for a few small improvements. A technician from MB company, which is the paint truck manufacture, also came to Fayetteville, NC to help the setting up process so that the trucks could be properly used.

The MB paint truck can hold 210 gallons of paint materials in each of the two tanks. One tank contains white paint and the other is for yellow paint. Paint materials from a manufacturer are usually contained in 30 gallons cans so the paint truck can hold 14 cans of paint. Normally 210 gallons of yellow paint are enough for one day use and about 400 gallons of white paint are used, so additionally several cans of white paint are carried to the field by another truck. The paint materials are manufactured by N. C. Department of Correction in Smithfield, NC. It should be noted that the whole state uses the same paint that supplied by N. C. Department of Correction. Thus, there should be excellent uniformity in paint materials used statewide by NCDOT personnel.

One paint truck requires 4-5 crew members to operate. The two paint trucks could run on different roads simultaneously during the paint season. Division 6 pavement marking crew members can be divided into three teams. Two teams operate the paint trucks and another small team installs preformed thermoplastic markings. The thermoplastic markings are applied by heating the material using a torch. These are relatively easy to install.

Division 6 personnel normally stripe the paint markings and install preformed thermoplastics. The division uses contractors to stripe molten thermoplastics and other markings. Paint markings normally are installed on secondary roads. Division 6 rotates striping paint markings from county to county and ensures that all roads are restriped in 1-3 years. Before restriping a road, a visual inspection by an experienced engineer is made to determine if the road actually needs to be restriped. Sometimes the engineer determines that the marking on the road is satisfactory for the current time, but may fail before the next visit to this area. If so, they will decide to restripe the markings.

Division 6 has good pavement marking practices. A test road leading to a roadway dead end is used for testing and calibrating the paint trucks. The paint guns and glass bead dispensers are adjusted on this road before striping other roads. Once adjusted, the trucks can be used for some time before requiring recalibration.

A conversation with the engineers reveals that on two-lane roads, two runs will finish the striping work. One run paints one white edge lines, and the other run paints the yellow center lines and the other white edge line.

14.2.8 National Workshop on Highway Asset Inventory and Data Collection Notes

Date: September 24-26, 2008 8:00 am – 5:00 pm
Location: Sheraton Imperial Hotel and Convention Center, Durham, NC 27703
Contacts: Neil Mastin, PMS Unit, NCDOT, (919)250-4096, jmastin@ncdot.gov
Omar Smadi, Iowa State University, (515)294-7110, smadi@iastate.edu

The national workshop on highway asset inventory and data collection is a three-day educational program on transportation asset management. The project team members John Zhang and Dr. Joseph Hummer participated in the workshop. Dr. Hummer gave a presentation at the workshop together with North Carolina Department of Transportation (NCDOT) engineers Jennifer Brandenburg and Brian Mayhew.

The workshop was an excellent opportunity to learn the state of art asset data collection techniques and asset management skills. The workshop consisted of a general introduction section on the first day, four technical sessions (pavement, bridge, roadside appurtenance, and geotechnical sessions) on the second day, and a closing section on the third day. The roadside appurtenance technical session was directly related to this pavement marking research project. Two presentations in this session addressed pavement marking data collection and asset management issues. They were summarized in the following paragraphs.

The presentation "Comparison of Automated and Manual Data Collection for Roadside Elements" by Jennifer et al. reported an effort to compare roadside data collected by typical manual methods to data collected by vehicles moving with traffic. NCDOT identified a 95-mile test course near Raleigh, NC. Data were collected on this test course. Pavement markings were a part of the roadside data items which included elements like curbs, guardrails, signs, and roadway geometry.

The variables collected for pavement marking included lateral location, color, width, type, and retroreflectivity. The vendors identified marking color well but had difficulty to determine the marking material type and width change. The manual retroreflectivity measurements were collected by a handheld retroreflectometer LTL-X. One vender collected retroreflectivity data by using a mobile retroreflectometer LaserLux. The reported average retroreflectivity difference was 36 mcd/m^2/lux (or 13% difference) between manual data collection and mobile data collection. This comparison was beneficial to our research because we used data collected both by a handheld unit and by a mobile unit.

Omar Smadi from Iowa State University gave a presentation named "Pavement Marking Data Collection Techniques". Dr. Smadi demonstrated some high speed videos which exhibited the bead application process. The videos showed how glass beads roll on the paint marking surface when sprayed from a bead gun. The videos were helpful in understanding pavement marking performances in a microscopic perspective. Then, Dr. Smadi introduced how they used image processing technology analyzing pavement marking durability. He also showcased the pavement marking management system they developed for the states of Iowa and Minnesota. Their research effort is related to this project.

14.2.9 <u>2009 TRB Annual Meeting Trip Report</u>

January 10-14, 2009, Washington, D.C.

Sessions and Meetings Related to Pavement Marking Research

- **AHD55 Pavement Marking Research Poster Session**
  - Six posters are exhibited in this session. Two research papers are closely related to the NCDOT research project.
    - One is “Evaluating Factors that May Influence Accuracy of Mobile Retroreflectivity Data Collection (09-0493).” The results of this paper show that mobile retroreflectometer performs well if properly calibrated.
    - Another poster is “Driver Performance and Safety Effects of Edge Lines on Rural Two-Lane Highways (09-0751).” This research finds that the edge line markings may reduce crash frequency on rural two lane highways with highest safety impacts occurred on curved roadway segments. .

- **AHD 55 In Situ Pavement Marking and Pavement Marker Evaluations Presentation Session**
  - Three presentations are on pavement markings, one is on pavement markers.
  - One paper evaluated 90-mil thermoplastic retroreflectivity performance during the early application period in Tennessee. The research is related to the current NCDOT project. However they only collected retroreflectivity data for 3 years in the early stage of thermoplastic life cycle.
  - Other two papers evaluated inlay thermoplastics and no-track thermoplastics

- **AHD 55 Advance in Pavement Marking Application, Testing, Inspecting, and Research**
  - Omar Smadi from Iowa State University showed high speed videos of paint marking application. Their paper “Pavement Marking Application: Bead Gun Evaluation Study Using a High-Speed Camera” is very innovative and is closely related to our current research on paint bead density.
  - Paul Carlson’s paper “Benefits of Pavement Markings: Renewed Perspective Based on Recent and Ongoing Research” was a good summary of the pavement marking research status and future research needs.
  - Eric Donnell from Pennsylvania State University presented how they use accelerated wear testing method to evaluate pavement marking performance. The test is innovative and looks like to be a good lab testing method.
  - Another presenter Masayuki Hirasawa was from Japan. He introduced how they determine marking repainting criteria in Japan

- **AHD 55 Signing and Marking Materials Committee Meeting**
  - FHWA is working on the minimum retroreflectivity standard for pavement markings. The exact date to include the retroreflectivity minimum values in MUTCD has not been decided.

- Two ASTM standards on pavement marking testing will be published soon.
- The TRB visibility symposium will be held on May 12-14, 2009 at Virginia Tech.

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14.2.10 IRM Third Annual PM Symposium for Senior Professional Managers Notes

Date: March 31, 2009
Location: Hilton Charlotte Executive Park, Charlotte, NC 28217
Contacts: Jim Cannon, Interstate Road Management (IRM), (570)455-1200
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The intersect road management (IRM) Third Annual Pavement Marking Symposium for Senior Professional Managers was a two day event which was held in Charlotte, NC. Project team members John participated in the symposium on March 31, 2009. The first day symposium consisted of four presentations and a short session of equipment demonstration.

The symposium is an excellent opportunity to know what other researchers are working on and what equipments the industry is utilizing. Paul Carlson from Texas Transportation Institute (TTI) introduced their three research projects on wet pavement marking performance and safety effects of pavement markings. Bill Toothill from DeAngelo Brothers introduced their research on GIS/GPS solutions for pavement marking mangers. Omar Smadi and Neal Hawkins presented their research efforts conducted in Iowa.

The presentation "Wet Retroreflectivity Pavement Markings" by Paul Carlson reported three research projects they have conducted on wet pavement markings. They designed and built a rain tunnel on a road near Texa A&M University where they can control the raining rate. The rain tunnel was the first in its kind built specifically for measuring pavement markings. Paul Carlson also reported their work on a new ASTM standard for measuring marking retroreflectivity under continues raining conditions. Carlson also mentioned that Florida is testing a new type of pavement markings which are designed to have good wet retroreflectivity values. The glass beads have a refractive index 1.5-1.9.

Omar Smadi and Neal Hawkins from Iowa State University gave a presentation named "Pavement Marking Data Collection Techniques". Smadi demonstrated some high speed videos which exhibited the bead application process. The videos showed how glass beads roll on the paint marking surface when sprayed from a bead gun. They used the video to evaluate the performance of different bead gun and the effects of striping speeds on the retroreflectivity. Then, they also showcased the pavement marking management system they developed for the states of Iowa and Minnesota.

The second presentation by Carlson introduced a study they conducted on the effects of wider pavement marking lines (6 inch). The conclusion form that study is that wider pavement markings are most cost effective when applied on two-lane highways. The traffic crash rates reduced 7% based on a before-and-after study. Carlson estimated that the cost of wider pavement markings (6 inch) is 20% more than normal markings (4 inch) though the material cost would be 50% more than 4 inch pavement markings.